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THE FUNDAMENTAL LAW OF ROAD CONGESTION: EVIDENCE FROM US CITIES

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ABSTRACT

We investigate the relationship between interstate highways and highway vehicle kilometers traveled (VKT) in US cities. We find that VKT increases proportionately to highways and identify three important sources for this extra VKT: an increase in driving by current residents; an increase in transportation intensive production activity; and an inflow of new residents. The provision of public transportation has no impact on VKT. We also estimate the aggregate city level demand for VKT and find it to be very elastic. We conclude that an increased provision of roads or public transit is unlikely to relieve congestion.

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1. Introduction

We investigate the effect of lane kilometers of roads on vehicle-kilometers traveled (VKT) for different types of roads in US cities. For interstate highways in the densest parts of metropolitan areas we find that VKT increases in exact proportion to highways, confirming the 'fundamental law of highway congestion' suggested by Downs (1962, 1992). This relationship also approximately holds for other important roads in dense areas and for interstate highways in less dense parts of metropolitan areas. These findings and others in the paper imply something broader than Down's law, a law of road congestion that applies to highways and major urban roads in metropolitan areas. In turn, this suggests that increased provision of highways and major urban roads is unlikely to relieve congestion of these roads.

Our investigation is of interest for three reasons. First, an average American household spent 161 person-minutes per day in a passenger vehicle in 2001. These minutes allowed 134 person-km of auto travel at an average speed of 44 km/h. Comparison with corresponding data from 1995 show that the time spent on routine household travel increased by 10% in only six years, while distances remained constant. Multiplying by the number of households in the US and any reasonable dollar value of time, we see that society allocated billions of dollars more to traffic congestion in 2001 than in 1995. That Americans rank commuting among their least enjoyable activities (Krueger, Kahneman, Schwarz, and Stone, 2008) confirms our suspicion that the costs of congestion are large. To the extent that these resources could have been better allocated, understanding congestion and the effect of potential policy interventions is an important economic problem.

Second, traffic is of considerable interest to policy makers, and given the high costs of traffic and road infrastructure, transportation policy should be based on the careful analysis of high quality data, not on the claims of advocacy groups. Unfortunately, there is currently little empirical basis for accepting or rejecting the claims of the *American Road and Transportation Builders Association* that "adding highway capacity is key to helping to reduce traffic congestion", or of the *American Public Transit Association* that without new investment in public transit, highways will become so congested that they "will no longer work".[1] We find that our data does not support either of these claims.

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[1] The quote from the APTA is at `www.apta.com/government_affairs/aptatest/documents/testimony060921.pdf`. The quote from the ARTBA is harder to find and occurs in an undated flyer which is no longer available on their website, http://www.artba.org/.

Third, with the increasing certainty of global warming comes the need to manage carbon emissions. According to the US Bureau of Transportation Statistics (2007, chapter 4) the road transportation sector accounts for about a third of US carbon emissions from energy use. Understanding the implications for VKT of changes to transportation infrastructure is immediately relevant to this policy problem.

Ours is not the first attempt to measure the effect of the supply of roads on traffic. Following Jorgensen (1947), a large literature estimates new traffic for particular facilities after their opening or after a capacity expansion (see Goodwin, 1996, Cervero, 2002, for reviews).[2] However studies of a particular road provide little basis for assessing the impact that changes in infrastructure have on traffic in the city at large, a question that is probably more relevant to transportation policy. As Cervero's (2002) review shows, few studies take an approach similar to ours and assess the effect of road provision on traffic over entire areas. These studies generally find a positive elasticity of VKT to the supply of roads, although they differ greatly regarding the magnitude of this elasticity. We improve on this literature in four respects.

First, we use more and more comprehensive data. To begin, we take average annual daily traffic (AADT) and a description of the road network from the US Highway Performance and Monitoring System (HPMS) for 1983, 1993, and 2003. We add a description of individual and household travel behavior taken from the National Personal Transportation Survey (NPTS) in 1995 and 2001. These data track several measures of traffic and infrastructure for all metropolitan areas in the continental US. Together with data describing truck traffic, public transit, sectoral employment, population and physical geography, these data are a powerful tool with which to investigate the way that VKT responds to changes the stock of highways and transit in US metropolitan areas. Extant research, on the other hand, examines one specific state (usually California) or a small sub-group of adjacent states (usually on the East coast) taking counties or smaller administrative units as the unit of observation.[3] The resulting estimates of the relationship between infrastructure and traffic in small administrative districts from highly urbanized parts of the US are not obviously relevant to national transportation policy.

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[2] While Jorgensen (1947) is our first modern source, the analysis of the effects of new facilities such as bridges and their tariffs on flows of vehicles follows a much older tradition, dating back to Dupuit (1844).

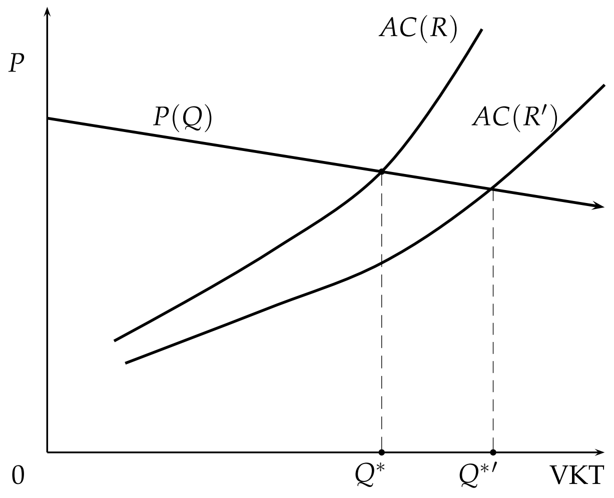
[3] Noland (2001) looks at data for the entire US but uses states as units of observation. Since roads in San Francisco or Buffalo are unlikely to affect behavior in Los Angeles or New York City, states appear to be 'too large' a unit of observation for two reasons: states aggregate city level variation that is useful for inference and the relevant economic unit appears to be the city.

Second, we are more careful to establish a causal relationship between roads and traffic. Existing literature either does not recognize that roads and traffic may be simultaneously determined or fails to solve this identification problem. To identify the causal effect of roads on traffic, we examine both time series and cross-sectional variation in our data and exploit three instrumental variables to predict the incidence of roads in MSAS. These instruments are based on; the routes of major expeditions of exploration between 1835 and 1850, major rail routes in 1898, and the proposed routes of interstate highways in a preliminary plan of the network. All estimations confirm the fundamental law of road congestion.

Third, beyond data and methodological improvements, we extend the conclusions of the existing literature in three ways. First, we show that the 'fundamental law of congestion' holds not only for urban interstates but also for major urban roads and non-urban interstates. Thus, our data suggest the following law of road congestion: adding road capacity will not alleviate congestion on any sort of major urban road or rural highway within metropolitan boundaries. Second, we deduce three further implications of the law of highway congestion and confirm that these implications are consistent with observation: when estimated directly, the demand for travel is close to being flat; metropolitan areas with less traffic experience a stronger increase in travel; the provision of public transportation has no impact on VKT. Third, we also document the factors underlying the fundamental law of highway congestion. Individuals drive more when the stock of roads in their city increases. Commercial driving and trucking increase with a city's stock of roads. People migrate to cities which are relatively well provided with roads. There is little substitution between different types of roads.

Finally, claiming, as is often done, that a high elasticity of VKT to roads automatically implies a low social value for the marginal road is wrong. We perform a detailed welfare calculation to assess the welfare gain from incremental increases to a city's stock of roads in the absence of congestion pricing. We find that the welfare gains for drivers of building more highways are well below the costs of building these highways. This conclusion follows, not from the high elasticity of VKT to roads, but from the fact that new roads do not reduce the cost of travel sufficiently.

Figure 1: Supply and demand for interstate traffic.



2. Roads and traffic: a simple framework

To motivate our econometric strategy consider a simple model of equilibrium VKT. To begin, let R denote lane kilometers of roads in a city, let Q denote VKT, and let $P(Q)$ be the inverse demand for VKT. The downward sloping line in figure 1 represents an inverse VKT demand curve for a particular city.

Let $C(R,Q)$ be the total cost of VKT, Q, given roads, R. In equilibrium all drivers face the same average cost of travel. Holding lane kilometers constant at R, the average cost of driving increases with VKT. Hence, the average cost curve for VKT is upward sloping. This feature is well documented in the transportation literature (Small and Verhoef, 2007). The leftmost upward sloping curve in figure 1 represents the supply curve $AC(R)$ associated with roads R.[4]

Equilibrium VKT, $Q^*(R)$ is characterized by

$$P(Q^*) = \frac{C(R,Q^*)}{Q^*}. \tag{1}$$

That is, willingness to pay equals average cost.

Increasing the supply of road lane kilometers from R to R' reduces the average cost of driving for any level of VKT.[5] It thus shifts the average cost curve to the right. With R lane kilometers of

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[4] Strictly speaking, this is an average variable cost curve since it neglects fixed costs of building and maintaining roads.

[5] There are pathological examples where increases in the extent of a road network can reduce its capacity, in particular the 'Braess paradox' described in Small and Verhoef (2007).

roads in the city, the demand curve intersects with the supply curve at Q^*, the equilibrium VKT. With R' kilometers of highways, the corresponding equilibrium implies a VKT of Q'^*.

We would like to learn the effect of an increase in the stock of roads on driving in cities. Indexing cities by i and years by t, our problem may be stated as one of estimating,

$$\ln(Q_{it}) = A_0 + \rho_R^Q \ln(R_{it}) + A_1 X_{it} + \epsilon_{it}, \tag{2}$$

where X denotes a vector of observed city characteristics and ϵ describes unobserved contributors to driving. We are interested in the coefficient of R, the road elasticity of VKT, $\rho_R^Q \equiv \partial \ln Q / \partial \ln R$.

With data describing driving and the stock of roads in a set of cities, we can estimate equation (2) with OLS to obtain consistent estimates of ρ_R^Q, provided that $cov(R,\epsilon|X) = 0$. In practice, we hope that roads will be assigned to growing cities and fear that they are assigned to prop-up declining cities. In either case, the required orthogonality condition fails. Thus, we are concerned that estimating equation (2) will not lead to the true value of ρ_R^Q.

As a next step, we partition ϵ into permanent and time varying components, and write

$$\ln(Q_{it}) = A_0 + \rho_R^Q \ln(R_{it}) + A_1 X_{it} + \delta_i + \eta_{it}. \tag{3}$$

With data describing a panel of cities, we can estimate this equation using city fixed effects to remove all time invariant city effects. This leads to consistent estimates of ρ_R^Q, provided that $cov(R,\eta|X,\delta) = 0$. We also estimate the first difference equation,

$$\Delta \ln(Q_{it}) = \rho_R^Q \Delta \ln(R_{it}) + A_1 \Delta X_{it} + \Delta \eta_{it}, \tag{4}$$

where Δ is the first difference operator. Since all time invariant factors drop out of the first difference equation, we are left with essentially the same orthogonality requirement as for equation (3).[6] An advantage of (4) is that city characteristics and initial VKT can readily be introduced in levels as explanatory variables in the regression.[7]

To our knowledge, there is no study of a comprehensive set of metropolitan areas in the literature. The extant literature, however, has estimated variants of equations (2), (3), and (4) on a small samples of counties or metropolitan areas. While the early literature on induced demand at the area level (e.g. Koppelman, 1972) only ran simple OLS regressions in the spirit of equation (2), second generation work on the issue typically explored a variety of specifications with fixed

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[6] In fact, the two estimates have subtly different properties, see Wooldridge (2001, chapter 4).

[7] This is useful if, for instance, ΔR is a response to initial VKT.

effects and, sometimes, a complex lag structure. For instance, Hansen, Gillen, Dobbins, Huang, and Puvathingal (1993) and Hansen and Huang (1997) use panels of urban counties and MSAs in California whereas Noland (2001) use a panel of US states. They all find a positive association between VKT and lane kilometers of roadway with a coefficient generally ranging between 0.3 and 0.7.

While the estimating equations (3) and (4) improve upon equation (2), we are concerned that roads will be assigned to cities in response to a contemporaneous shock to the city's traffic. To deal with this identification issue, we need to model the assignment of roads to cities explicitly. This leads to a two equation model, one to predict the assignment of roads to cities, the other to predict the effect of roads on traffic,

$$\begin{aligned} \ln(R_{it}) &= B_0 + B_1 X_{it} + B_2 Z_{it} + \mu_{it} \\ \ln(Q_{it}) &= A_0 + \rho_R^Q \widehat{\ln(R_{it})} + A_1 X_{it} + \epsilon_{it}. \end{aligned} \tag{5}$$

We can obtain unbiased estimates of ρ_R^Q provided that we are able to find instruments to satisfy $cov(Z,R|X) \neq 0$ and $cov(Z,\epsilon|X) = 0$.

The possible simultaneous determination of VKT and lane kilometers is recognized by several authors. To instrument for lane kilometers of highways Cervero and Hansen (2002) use a range of 20 or so instruments, from politics to natural geography. The exclusion restriction needed to obtain unbiased estimates, namely that the instruments are correlated with VKT only through lane kilometers is unlikely to hold. Aside from the econometric issues associated with the use of a large number of instruments, we expect the geographic characteristics of cities, and more particularly climatic variables, to predict the demand for travel directly in addition to the indirect effect via road supply. This violates the condition $cov(Z,\epsilon|X) = 0$ and invalidates the instruments. Noland and Cowart (2000) use land area and population density as instruments for lane kilometers of roads. Again, we expect population density to be a determinant of the demand for travel as much as a determinant of the supply of roads. Fulton, Noland, Meszler, and Thomas (2000) instrument growth in lane kilometers of highways by short lags of the same variables in a first difference specification. The exclusion restriction then requires that past changes in road supply be uncorrelated with contemporaneous changes in demand. Since changes in road supply are serially correlated (and they need to be so for the instrument to have any predictive power), the exclusion restriction is unlikely to hold when new roads are supplied as a result of demand shocks. We postpone a discussion of our own choice of instruments.

Each of the approaches described above relies on different variation in the data to estimate ρ_R^Q. Equation (2) relies on cross-section variation, while equations (3) and (4) use only time series variation. Equation (5) exploits the instrumental variables we describe later. Should all three methods arrive at the same estimate of ρ_R^Q, then either all must be correct, or all are incorrect and an improbable relationship exists between the various errors and instrumental variables.

We now turn to a description of our data and estimates of ρ_R^Q based on the estimating equations presented in this section.

3. Data and estimation

We take the (Consolidated) Metropolitan Statistical Area (MSA) drawn to 1999 boundaries as our unit of observation. Since each MSA aggregates one or more counties their boundaries often encompass much land that is not 'urban' in the common sense of the word. However, MSAs are generally organized around one or more 'urbanized areas' which make up the cores of the MSA and typically occupy only a fraction of an MSA's land area. By using data collected at the level of 'urbanized areas' we can distinguish more from less densely developed parts of each metropolitan area.

To measure each MSA's stock of highways and traffic we use the US Highway Performance and Monitoring System (HPMS) 'Universe' and 'Sample' data for 1983, 1993, and 2003.[8] The separate data appendix provides more details about the HPMS. The US Federal Highway Administration collects these data, which are used by the federal government for planning purposes and to apportion federal highway money. Each year, states must report the length, number of lanes and the average annual daily traffic (AADT) for the entire universe of the interstate highway system within their boundaries. We use a county identifier to match every segment of interstate highway to an MSA. We then calculate lane kilometers, VKT and AADT per lane km for interstate highways within each MSA. In the Sample data states must report the same information (and more) for every segment of interstate highway within urbanized areas. By merging the Sample with the Universe data we distinguish urban from non-urban interstates within MSAs.

The Sample data also report information about a sample of other roads within urbanized areas. This sample is intended to represent all roads in urbanized areas within the state. For each sampled

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[8] In fact, the HPMS is available annually. We focus on 1983, 1993 and 2003 because these dates are close to census years and to the years for which we have data on public transportation. In addition to these three years, we sometimes make use of the 1995 and 2001 HPMS.

Table 1: Summary statistics for our main HPMS and public transportation variables (averaged over MSAs, means and standard deviations between brackets).

Year:	1983	1993	2003
Mean daily VKT (IH,'000 km)	7,777	11,905	15,961
	(16,624)	(24,251)	(31,579)
Mean AADT (IH)	4,832	7,174	9,361
	(2,726)	(3,413)	(4,092)
Mean lane km (IH)	1,140	1,208	1,280
	(1,650)	(1,729)	(1,858)
Mean lane km (IH, per 10,000 pop.)	26.7	24.3	22.1
	(26.9)	(20.9)	(16.4)
Mean daily VKT (MRU,'000 km)	14,553	22,450	31,242
	(36,303)	(49,132)	(70,692)
Mean AADT (MRU)	3,146	3,646	3,934
	(847)	(947)	(1,059)
Mean lane km (MRU)	3,885	5,071	6471
	(7,926)	(9,119)	(12,426)
Mean VKT share urbanized (IHU/IH)	0.38	0.44	0.48
Mean lane km share urbanized (IHU/IH)	0.29	0.36	0.40
Mean share truck AADT (IH)	0.11	0.12	0.13
Peak service large buses per 10,000 pop.	1.20	1.09	1.34
	(1.02)	(0.98)	(0.98)
Peak service large buses	169	165	217
	(563)	(562)	(742)
Number MSAs	228	228	228
Mean MSA population	753,726	834,290	950,054

IH denotes interstate highways for the entire MSA. IHU denotes interstate highways for the urbanized areas within an MSA. MRU denotes major roads for the urbanized areas within an MSA.

segment in an urbanized area, the HPMS Sample data reports the road's length, location, AADT and share of truck traffic. The HPMS sample data also assigns each segment to one of six functional classes, described in US Federal Highway Administration (1989). One of these classes is 'interstate highway'. We group four of the remaining five classes; 'collector', 'minor arterial', 'principal arterial', and 'other highway' into a measure of major urban roads, omitting the last class, 'local roads'.[9] Our definition of 'major urban road' thus includes all non-local roads that are not interstate highways. Within urbanized areas, interstates represent about 1.5% of all road kilometers and 24% of VKT while major urban roads represent 27% of road kilometers and another 62% of VKT (United States Federal Highway Administration, 2005). The separate data appendix provides more detail.

Table 1 presents MSA averages of AADT for the 228 MSAs with non-zero interstate milage in 1983, 1993, and 2003. These data show that AADT increased from 4,832 vehicles on an average lane kilometer of interstate highway on an average day in 1983 to 9,361 in 2003. Thus, at the end of our study period, an average lane kilometer of interstate highway carries almost twice as much traffic

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[9] Loosely, a 'local road' is one that primarily provides access to land adjacent to the road and every other class of road serves to connect local roads. The HPMS does not require states to report data on local roads, although some local roads appear in the data.

as at the beginning. We also find that lane kilometers of interstate highways increase by about 6% between 1983 and 1993 and between 1993 and 2003. Together, the increase in lane kilometers and the increase in AADT imply that interstate VKT in an average MSA more than doubled over our twenty year study period.

Table 1 also presents descriptive statistics for major urban roads. Major roads represent between three and five times as many lane kilometers as interstate highways but only twice as much VKT. Note that urbanized area boundaries, unlike MSA boundaries, are not constant over our three cross-sections, so the dramatic increase in urbanized area VKT and lane kilometers over our study period may partly reflect increases in the extent of urbanized areas.

Cross-sectional estimates of the roadway elasticity of VKT

We now turn to estimating the elasticity of MSA VKT to lane kilometers for each of the following categories of roads and travel: All MSA interstates (IH), urbanized MSA interstates (IHU), non-urban MSA interstates (IHNU), and major urban roads (MRU).

Columns 1-5 of table 2 present estimates of the four elasticities obtained by pooling our three cross-sections and estimating equation (2) for each type of road.

In panel A of this table, the dependent variable is MSA interstate VKT. In the first column we include only a constant and year dummies. In the second we add MSA population. In the third, we add nine census division dummy variables along with five measures of physical geography described in the separate data appendix: elevation range within the MSA, the ruggedness of terrain in the MSA, two measures of climate, and a measure of how dispersed is development in the MSA. In column 4 we add socio-economic controls (share of population with at least some college education, log mean income, share poor, share of manufacturing employment, and an index of segregation). In column 5 we also add decennial population variables from 1920-1980.[10] The elasticity of interstate highway is 1.24 in column 1, ranges between 0.82 and 0.86 in the other specifications, and is estimated precisely in each specification.

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[10] We also experimented with gasoline price data kindly given to us by Kent Hymel, Ken Small, and Kurt van Dender. Adding gasoline prices changed nothing to our results regarding ρ_R^Q. On the other hand, the coefficient on gasoline price is imprecisely estimated and sensitive to the exact specification. This is not surprising since states might be using state taxes on gasoline to deal with congestion. The proceeds of this taxation also indirectly serve to finance road construction. We do not report these results here.

Table 2: VKT as a function of lane kilometers, pooled OLS.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A. Dependent variable: ln VKT for interstate highways, entire MSAs								
ln(IH lane km)	1.24^a	0.82^a	0.86^a	0.85^a	0.85^a	1.05^a	1.06^a	1.05^a
	(0.02)	(0.05)	(0.05)	(0.04)	(0.04)	(0.05)	(0.05)	(0.05)
ln(pop.)		0.48^a	0.44^a	0.47^a	0.32^a		0.34^a	0.39^a
		(0.04)	(0.04)	(0.04)	(0.12)		(0.10)	(0.10)
Elev. range			-0.031	-0.055	-0.049			
			(0.05)	(0.05)	(0.05)			
Ruggedness			6.18^b	6.13^b	4.33			
			(3.04)	(2.88)	(2.85)			
Heating d.d.			-0.013^a	-0.013^a	-0.015^a			
			(0.00)	(0.00)	(0.00)			
Cooling d.d.			-0.019^b	-0.019^b	-0.025^a			
			(0.01)	(0.01)	(0.01)			
Sprawl			0.0036	0.0043	0.0032			
			(0.00)	(0.00)	(0.00)			
Census div.			Y	Y	Y			
Socio-econ. char.				Y	Y			Y
Hist. pop.					Y			
MSA fixed effects						Y	Y	Y
R^2	0.88	0.94	0.95	0.95	0.95	0.94	0.94	0.95
Panel B. Dependent variable: ln VKT for interstate highways, urbanized areas within MSAs								
ln(IHU lane km)	1.23^a	0.98^a	1.00^a	1.00^a	1.01^a	0.99^a	0.99^a	0.98^a
	(0.02)	(0.03)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)
Panel C. Dependent variable: ln VKT for Major Roads, urbanized areas within MSAs								
ln(MRU lane km)	1.12^a	0.83^a	0.84^a	0.83^a	0.84^a	0.89^a	0.88^a	0.88^a
	(0.01)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.04)	(0.04)
Panel D. Dependent variable: ln VKT for interstate highways, outside urbanized areas within MSAs								
ln(IHNU lane km)	1.03^a	0.82^a	0.84^a	0.85^a	0.83^a	0.97^a	0.97^a	0.96^a
	(0.03)	(0.03)	(0.03)	(0.03)	(0.02)	(0.03)	(0.03)	(0.03)

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 684 observations corresponding to 228 MSAs for each regression in panel A and 576 (192 MSAs) in panels B-D. *a*, *b*, *c*: significant at 1%, 5%, 10%.

It is interesting to note that the population elasticity of VKT is much less than one in all specifications. This will persist in nearly all of our estimations and suggests that people in larger cities drive much less, per capita, than they do in smaller cities. We consider the effect of population and the possible endogeneity of this variable further below. VKT is higher in MSAs with mild weather, neither cold nor hot. The extent to which development is scattered or compact, as measured by the variable 'sprawl', does not affect VKT.

Panel B of table 2 is similar to panel A, but the dependent variable and the measure of roads are based on *urban* interstates. The estimations in panel B suggest that the urban interstate VKT elasticity of urban interstate lane kilometers is close to one and slightly larger than for all interstates. Panels C and D of table 2 are also similar to panel A, but investigate major urban roads and non-urban interstates. These results are also similar to those presented in panel A.

Note that panel A of table 2 is based on the 228 MSAs which report interstate highways in all three of our sample years. Panels B, C, and D use a slightly smaller sample, which excludes MSAs which do not have urban interstate highways in all years. In appendix table 1 (in a separate appendix), we replicate panel A on this restricted sample. The results are similar to those reported in the text, so we do not concern ourselves with sample selection. Appendix table 2 reports regressions similar to those reported in table 2, but uses each cross-section separately. The results of table 2 are preserved for each of our three cross-sections.

Time series estimates of the roadway elasticity of VKT

Thus far we have reported estimates of ρ_R^Q which exploit cross-sectional variation. We now turn to estimates of ρ_R^Q based on time series variation.

Columns 6-8 of table 2 estimate equation (3) by including an MSA fixed effect in our cross-sectional regression. In column 6 we include only an MSA fixed effect and time dummies as controls. In column 7, we add MSA population. In column 8, we add our other time varying MSA level demographic variables. In panel A, we see that all of the fixed-effect estimates of the interstate VKT elasticity of interstate lane kilometers are slightly above one. While it is estimated precisely in all three specifications, ρ_R^Q is not statistically different from one at standard levels of confidence in any of the three.

In panels B-D, columns 6-8 repeat the estimates presented in panel A, but use urban interstates, major urban roads, and non-urban interstates. In each case we find the relevant VKT elasticity of roads is close to one, and is estimated precisely. As for table 1, note that, although MSA boundaries are constant over our three cross-sections, urbanized area boundaries are not.

We now estimate the interstate VKT elasticity of interstate lane kilometers using our first difference estimating equation (4). Using our three cross-sections we compute two cross-sections of first differences. In table 3 we pool these two cross-sections of first differences to estimate equation (4). Our dependent variable is the 10 year change in interstate VKT. In column 1, we include only a constant and year dummies as controls. In column 2, we add MSA population. In column 3, we also control for initial VKT. In column 4, we add physical geography and census division dummies. Column 5 adds decennial MSA population levels from 1920-1980 and initial socioeconomic characteristics of cities. In each case, our point estimate of ρ_R^Q is very close to one

Table 3: Change in VKT as a function of change in lane kilometers, OLS.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
Dependent variable: $\Delta \ln$ VKT for interstate highways, entire MSAs										
$\Delta \ln$(IH lane km)	1.04^a	1.05^a	1.02^a	1.00^a	0.93^a	1.03^a	1.03^a	1.09^a	0.90^a	0.82^a
	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)	(0.05)	(0.05)	(0.06)	(0.06)	(0.09)
$\Delta \ln$(pop.)		0.34^a	0.40^a	0.44^a	0.39^a		0.51^b	0.31^c	0.45^b	0.16
		(0.10)	(0.10)	(0.11)	(0.13)		(0.20)	(0.17)	(0.21)	(0.22)
ln(initial VKT)			-0.047^a	-0.057^a	-0.12^a				-0.15^a	-0.13^a
			(0.01)	(0.01)	(0.02)				(0.03)	(0.04)
Geography				Y	Y				Y	Y
Census div.				Y	Y				Y	Y
Socio-econ. char.					Y				Y	Y
Hist. Pop.					Y				Y	Y
MSA fixed effects						Y	Y			
R^2	0.87	0.87	0.89	0.90	0.91	0.87	0.88	0.91	0.94	0.69

All regressions include a constant and decade effects. Robust standard errors clustered by MSA in parentheses. 456 observations for each regression in columns 1-7, 205 in columns 8-9 which consider only increases in lane kilometers of more than 5%, and 115 in column 10 which considers declines in lane kilometers greater than 5%. *a*, *b*, *c*: significant at 1%, 5%, 10%.

and is precisely estimated.

Column 6 of table 3 estimates equation (4) including an MSA fixed-effect and year fixed effects as controls, while column 7 adds MSA population. These estimates are second difference estimates which exploit changes in the rate of change of roads and traffic. Strikingly, these regressions also estimate the interstate VKT elasticity of interstate highways to be very close to one.

Finally, columns 8-10 consider more restricted samples of observations. Column 8 replicates column 2 using only observations with increases in lane kilometers greater than 5%. Column 9 uses the same selection rule to replicate column 5. Column 10 replicates column 5 again but this time using only observations with declines in lane kilometers greater than 5%. The results for large increases in lane kilometers are the same than for the whole sample of MSAs. The elasticity we estimate in column 10 is 0.8. These estimations do not allow us to determine whether the response of traffic to roads is non-linear in the amount of change to the road network, or if metropolitan areas experiencing large changes are different from those experiencing small changes.

As a check on our pooled first difference estimations, appendix table 3 in the separate appendix presents first difference regressions conducted on each of our two cross-sections of first differences. Appendix table 4 extends the results of table 3 to other types of roads. In appendix table 5 we show that changes in VKT between 1993 and 2003 are not explained by changes in lane kilometers of interstate highways between 1983 and 1993. This suggests that VKT completely adjusts to changes in the road network in less than 10 years. Finally, in appendix table 6 we instrument for population changes using initial sectoral composition of economic activity interacted by the national growth in sectoral employment in the spirit of Bartik (1991) and others after him. This does not affect our estimates of ρ_R^Q either.

IV *estimates of the roadway elasticity of* VKT

In order for estimates of equation (2) and (3) to result in unbiased estimates, we require that the unobserved error be uncorrelated with the stock of roads (or changes in this stock). If the demand for VKT helps to determine an MSA's road network, then our measure of roads is endogenous, and this assumption does not hold. To address this possibility, we estimate the instrumental variables system described in equation (5).

We rely on three instruments: planned highway kilometers from the 1947 highway plan; 1898 railroad route kilometers, and the incidence of major expeditions of exploration between 1835 and 1850. Baum-Snow (2007), Michaels (2008), and Duranton and Turner (2008) also use planned interstates as an instrument for features of the interstate system. Duranton and Turner (2008) use the 1898 railroad system for the same purpose. The exploration routes variable is new to the literature.[11]

Our measure of MSA kilometers of 1947 planned interstate highways is based on a digital image of the 1947 highway plan created from its paper record (United States House of Representatives, 1947) and converted to a digital map as in Duranton and Turner (2008). Kilometers of 1947 planned interstate highway in each MSA are calculated directly from this map. Figure 2 shows an image of the original plan. Our measure of MSA kilometers of 1898 railroads is based on a digital image of a map of major railroad lines in 1898 (Gray, c. 1898). This image was converted to a digital map as in Duranton and Turner (2008). Kilometers of 1898 railroad contained in each MSA are calculated directly from this map. Figure 3 shows an image of the original railroad map. Our measure of early exploration routes is based on a map of routes of major expeditions of exploration of the US between 1835 and 1850 (United States Geological Survey, 1970). An image based on this map is reproduced in figure 4. Note that, in addition to exploration routes, this map also shows the routes of major roads established prior to 1835 in the more settled eastern part of the country. The separate data appendix provides more detail about these variables.

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[11] The discussion of the 1947 highway plan and 1898 railroad routes is derived from, and abbreviates more extensive discussions of these variables by these earlier authors, particularly Duranton and Turner (2008).

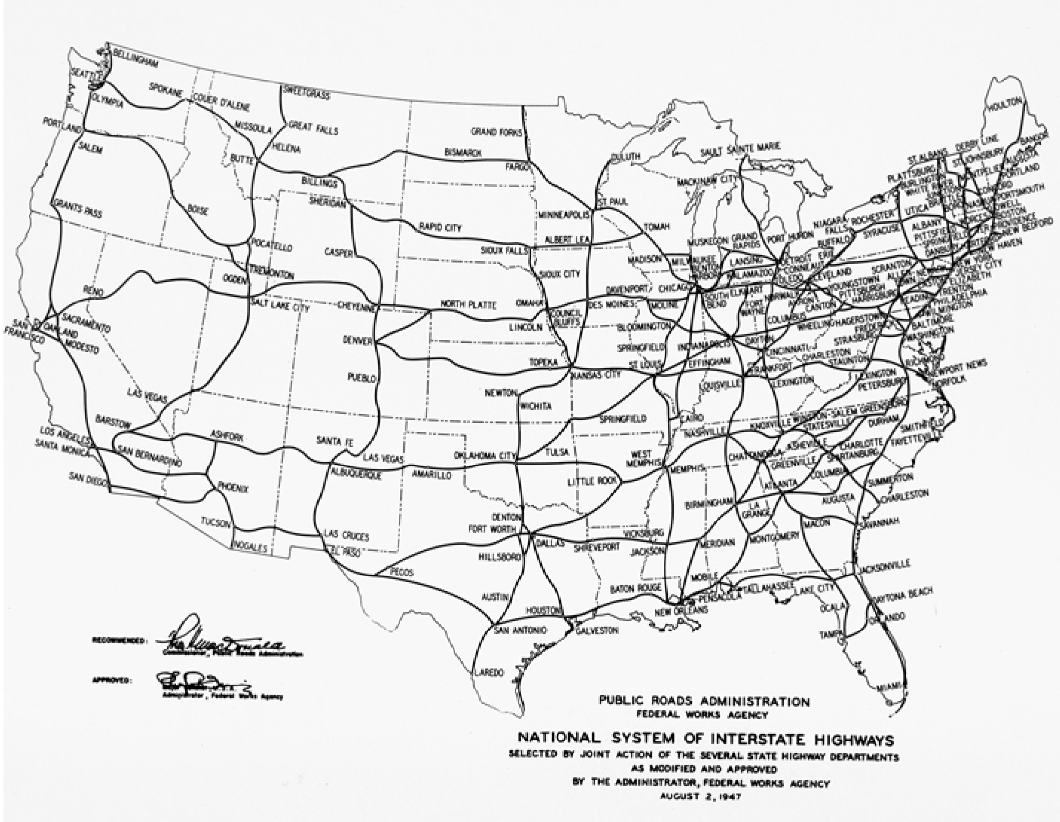

Figure 2: 1947 US interstate highway plan.

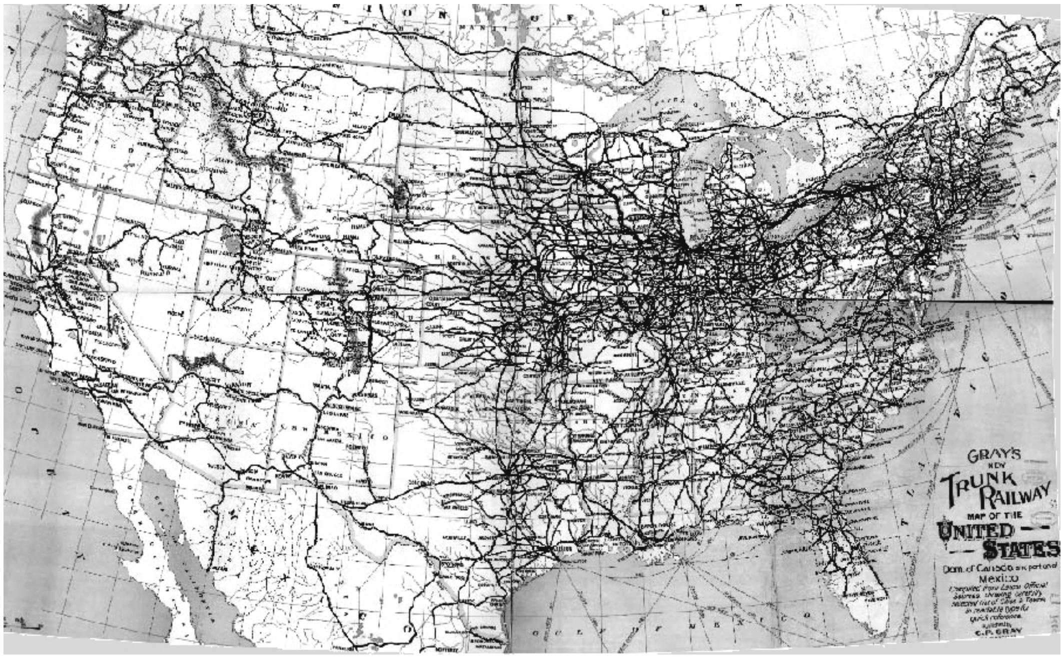

Figure 3: Image based on Gray's map of 1898 railroads (Gray, c. 1898).

Figure 4: Routes of major expeditions of exploration in the US between 1835 and 1850. Image based on United States Geological Survey (1970) [p. 138].

Common sense suggests that all three instruments should be relevant. The 1947 plan describes many highways that were subsequently built. Many 1898 railroads were abandoned and turned into roads. Many current interstate highways follow the same routes taken by early explorers. Estimates of the reduced form equation predicting roads as a function of our instruments confirm this intuition. In almost all specifications predicting interstate lane kilometers, the first-stage statistic for the instrumental variables is large enough to pass the weak instrument tests proposed in Stock and Yogo (2005). We generally report the results of conventional TSLS estimations, but in the few cases where our instruments are weak, we also report the corresponding LIML estimates.

A qualifier is important here. Our instruments are good predictors of MSA level stocks of interstate highways and urban interstate highways. They are not good predictors of MSA level stocks of major roads or of non-urban interstate highways. For this reason, we conduct IV estimations only for interstate highways and urban interstate highways.

We now turn to the conditional exogeneity of our two instruments. The 1947 highway plan was first drawn to *'connect by routes as direct as practicable the principal metropolitan areas, cities and industrial centers, to serve the national defense and to connect suitable border points with routes of continental importance in the Dominion of Canada and the Republic of Mexico'* (United States Federal

Works Agency, Public Roads Administration, 1947, cited in Michaels, 2008). That the 1947 highway plan was, in fact, drawn to this mandate is confirmed by both econometric and historical evidence reviewed in Duranton and Turner (2008). In particular, in a regression of log 1947 kilometers of planned highway on log 1950 population, the coefficient on planned highways is almost exactly one, a result that is robust to the addition of various controls. On the other hand population growth around 1947 is uncorrelated with planned highway kilometers. Thus, the 1947 plan was drawn to fulfill its mandate and connect major population centers of the mid-1940s, not to anticipate future population or traffic demand.

Note that the exclusion restriction associated with equation (5) requires the orthogonality of the dependent variable and the instruments conditional on control variables. This observation is important. Cities that receive more roads in the 1947 plan tend to be larger than cities that receive fewer. Since we observe that large cities have higher levels of VKT, 1947 planned highway kilometers predicts VKT by directly predicting population and indirectly by predicting 1980 road kilometers. Thus the exogeneity of this instrument hinges on having an appropriate set of controls, population in particular.

Next consider the case for the exogeneity of the 1898 railroad network. This network was built, for the most part, during and immediately after the civil war, and during the industrial revolution. At this time, the US economy was much smaller and more agricultural than during our study period. In addition, the rail network was developed by private companies with the intention to make a profit from railroad operations in the not too distant future. See Fogel (1964) and Fishlow (1965) for two classic accounts of the development of US railroads. As for the highway plan, the same qualifying comment applies: instrument validity only requires that rail routes be uncorrelated with the dependent variable conditional on the control variables. With this said, after controlling for historical populations and physical geography, it is difficult to imagine how a rail network built for profit could anticipate the demand for vehicle travel in cities 100 years later save through its effect on roads.

Finally, consider the case for the exogeneity of routes of expeditions of exploration between 1835 and 1850. Among these routes are; a Mexican boundary survey, the Whiting-Smith 1849 search for a commercial route between San Antonio and El Paso, the 1849 Warner-Williamson expedition in search of a route from Sacramento to the Great Basin, the 1839 Farnham-Smith expedition from Peoria to Portland, and the Smith scientific expedition to the Badlands of South Dakota. Some of these expeditions were explicitly charged with finding an easy way from one place to another and it is hard to imagine that this objective was not also important to the others. While we expect that these early explorers were drawn to attractive places, after controlling for historical populations and physical geography it is difficult to imagine how these explorers could select routes that anticipate the demand for vehicle travel in cities 150 years later save through their effect on roads.

Table 4 presents instrumental variables estimations corresponding to the ols estimates presented in table 2. In panel a, our dependent variable is all msa interstate vkt, we use all three of our instruments, and we pool our three decennial cross-sections. Column 1 includes only interstate lane kilometers and decade effects as controls. Column 2 adds population as a control, column 3 adds our physical geography variables and census division indicators, column 4 adds our other city level demographic variables, and column 5 adds decennial population levels from 1920 to 1980. We pass standard over-id test in all specifications, and the values of our first-stage statistics suggest that they are either strong, or near the critical values suggested by Stock and Yogo (2005). Column 5 is our preferred estimate: This regression contains the strongest controls, so it is in this regression that we are most confident that our instruments satisfy the exclusion restriction, and hence that we obtain an unbiased estimate of ρ_R^Q. For interstate highways, this estimate is 1.04 with a standard error of 0.13. In columns 2 through 5 we see that our estimates of ρ_R^Q are within one standard error of 1. In column 1, the coefficient of highways is larger because of the correlation between highway lane kilometers and population levels.

With this said, in columns 3, 4, and 5 of panel a our instruments are near critical values suggested in Stock and Yogo (2005), so in panel b we present the corresponding liml estimates. These estimates are essentially identical to the tsls estimates of panel a.

In panels c, d, and e, we repeat the tsls estimates of panel a using each of our instruments alone. We find that using the 1947 highway instrument alone results in slightly higher estimates, that using 1898 railroads alone results in essentially identical estimates, and that using 1835 exploration routes alone results in slightly lower estimates. In all, the iv estimates presented in panels a-e of table 4 strongly suggest that the interstate vkt elasticity of interstate highways is close to one.

In panel f of table 4 we duplicate the regressions of panel a but use urbanized area interstate vkt as our dependent variable and urbanized interstate lane kilometers as our measure of roads. Except for column 1, which does not control for population, these estimates are also all within one

Table 4: VKT as a function of lane kilometers, IV.

	[1]	[2]	[3]	[4]	[5]
Panel A (TSLS). Dependent variable: ln VKT for interstate highways, entire MSAs. Instruments: ln 1835 exploration routes, ln 1898 railroads, and ln 1947 planned interstates					
ln(IH lane km)	1.32^{a}	0.92^{a}	1.03^{a}	1.01^{a}	1.04^{a}
	(0.04)	(0.10)	(0.11)	(0.12)	(0.13)
ln(pop.)		0.40^{a}	0.30^{a}	0.34^{a}	0.23^{c}
		(0.07)	(0.09)	(0.10)	(0.12)
Elev. range			-0.026	-0.051	-0.058
			(0.06)	(0.05)	(0.05)
Ruggedness			6.69^{c}	6.79^{b}	5.10
			(3.45)	(3.20)	(3.18)
Heating d.d.			-0.015^{a}	-0.014^{a}	-0.016^{a}
			(0.00)	(0.00)	(0.00)
Cooling d.d.			-0.022^{a}	-0.018^{b}	-0.029^{a}
			(0.01)	(0.01)	(0.01)
Sprawl			0.0013	0.0021	0.0011
			(0.00)	(0.00)	(0.00)
Census div.			Y	Y	Y
Socio-econ. char.				Y	Y
Hist. pop.					Y
Overid.	0.60	0.11	0.26	0.24	0.29
First stage Stat.	42.8	16.5	11.8	11.5	8.84
Panel B (LIML). Dependent variable: ln VKT for interstate highways, entire MSAs. Instruments: ln 1835 exploration routes, ln 1898 railroads, and ln 1947 planned interstates					
ln(IH lane km)	1.32^{a}	0.94^{a}	1.05^{a}	1.02^{a}	1.06^{a}
	(0.04)	(0.11)	(0.12)	(0.13)	(0.15)
Overid.	0.60	0.11	0.26	0.25	0.30
Panel C. (TSLS). Dependent variable: ln VKT for interstate highways, entire MSAs. Instruments: ln 1947 planned interstates					
ln(IH lane km)	1.33^{a}	1.00^{a}	1.10^{a}	1.08^{a}	1.12^{a}
	(0.05)	(0.11)	(0.13)	(0.13)	(0.15)
First stage Stat.	99.7	41.5	29.8	29.5	26.7
Panel D. (TSLS). Dependent variable: ln VKT for interstate highways, entire MSAs. Instruments: ln 1898 railroads					
ln(IH lane km)	1.31^{a}	0.83^{a}	1.03^{a}	1.00^{a}	1.02^{a}
	(0.06)	(0.15)	(0.18)	(0.18)	(0.22)
First stage Stat.	23.7	25.8	19.0	21.1	11.9
Panel E (TSLS). Dependent variable: ln VKT for interstate highways, entire MSAs. Instruments: ln 1835 exploration routes					
ln(IH lane km)	1.25^{a}	0.63^{a}	0.75^{a}	0.68^{a}	0.72^{a}
	(0.08)	(0.17)	(0.18)	(0.21)	(0.22)
First stage Stat.	53.6	13.8	9.91	7.15	6.32
Panel F (TSLS). Dep. var.: ln VKT for interstate highways, urbanized areas within MSAs. Instruments: ln 1835 exploration routes, ln 1898 railroads, and ln 1947 planned interstates					
ln(IHU lane km)	1.25^{a}	1.06^{a}	1.15^{a}	1.15^{a}	1.14^{a}
	(0.03)	(0.11)	(0.12)	(0.13)	(0.14)
Overid.	0.43	0.22	0.33	0.30	0.32
First stage Stat.	32.9	9.98	9.09	9.05	6.29

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 684 observations corresponding to 228 MSAs for each regression in panels A-E and 576 (192 MSAs) in panel F. *a*, *b*, *c*: significant at 1%, 5%, 10%.

standard deviation of one, although all of the point estimates are larger than the corresponding estimates in panel A. This suggests that the urbanized interstate VKT elasticity of urbanized interstate lane kilometers, ρ_R^Q, may be larger than for all interstates, and hence that this elasticity may be even larger than one.[12]

For all regressions in table 4 we pool our three cross-sections. This may conceal cross-decade variation in our parameters. To address this issue, appendix table 7 in a separate appendix reports IV estimates of ρ_R^Q using each of our cross-sections. These results confirm those reported in table 4.

4. Implications of the fundamental law of road congestion

We have so far presented direct evidence for the fundamental law of road congestion. We here note that this law has thee implications. By confirming these implications, we provide further indirect evidence of the law.

Perfectly elastic demand for VKT

The extant literature suggests that the long run cost of providing VKT is approximately constant returns to scale (Keeler and Small, 1977, Small and Verhoef, 2007). In the notation of section 2, this constant returns to scale condition is written $\lambda C(R,Q) = C(\lambda R, \lambda Q)$ for λ a positive scalar. If such constant returns holds, then the fundamental law of highway demand is equivalent to a perfectly elastic demand for VKT. To see this, restate the fundamental law of highway congestion as,

$$1+\lambda = \frac{Q^*((1+\lambda)R)}{Q^*(R)}. \tag{6}$$

That is, an increase in lane kilometers induces an exactly proportional increase in VKT. This statement of the fundamental law, together with constant returns to scale of C gives

$$\frac{C\left((1+\lambda)R,Q^*((1+\lambda)R)\right)}{Q^*((1+\lambda)R)} = \frac{C\left((1+\lambda)R,(1+\lambda)Q^*(R)\right)}{(1+\lambda)Q^*(R)} = \frac{C\left(R,Q^*(R)\right)}{Q^*(R)}. \tag{7}$$

It follows from our equilibrium condition (1) that $P(Q^*((1+\lambda)R)) = P(Q^*(R))$. That is, given constant returns to scale of $C(R,Q)$, the fundamental law of road congestion is equivalent to perfectly elastic demand for VKT.

In order to check this implication of the fundamental law of road congestion, we must estimate the price elasticity of VKT. That is, we would like to know how aggregate demand for VKT responds

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[12] ρ_R^Q is not bounded from above by one. An additional segment of roads can make a network more attractive. Alternatively, more lanes to relieve a particular bottleneck can increase travel on an entire road.

to changes in the price of travel. To begin, consider the demand by individual j for VKT in MSA i, $D_j(P_i, \cdot)$. While we imagine that this demand will also depend on the city's size, climate and geography, demand for travel also responds to the price of this travel. That is, the number of trips an individual takes to the store, or the length of his commute, depends on the unit cost of travel. As a first approximation, the extent of the road network does not enter directly into the individual's demand function except through its impact on the time per unit travel. This will be the identifying assumption that we use to distinguish the demand curve from the supply curve.

If we aggregate and then invert our individual demand curve, we are left with an aggregate inverse demand curve for MSA i,

$$\ln(P_i) \quad = \quad A_0 + \rho_Q^P \ln(Q_i) + A_2 X_i + \epsilon_i, \tag{8}$$

where ρ_Q^P is the VKT elasticity of the price.

The supply curve for VKT in MSA i describes the amount of travel that may be produced in an MSA at given cost. This is analogous to a standard supply curve, except that the open access nature of the network requires that the supply curve describe the way supply responds to changes in average cost rather than changes in marginal cost. Excluding pathological examples, the amount of travel produced in an MSA at a given unit time cost should increase with the extent of the road network. If we invert this supply relationship, we are able to write the unit cost of VKT as a function of the level of VKT, the extent of the road network, and other MSA characteristics such as climate, size and physical geography which also determine the cost of travel. That is, we have

$$\ln(AC_i) \quad = \quad B_0 + B_1 \ln(Q_i) + B_2 \ln(R_i) + B_3 X_i + \mu_i. \tag{9}$$

One problem remains. We are concerned that roads may be assigned to MSAs on the basis of unobserved characteristics which also affect supply or demand. In this case, R_i is correlated with the errors in both equations and standard techniques result in biased estimates of ρ_Q^P.

To avoid this problem, rather than include R_i as an explanatory variable in our supply relationship, we proxy for the stock of roads using our three instrumental variables. These variables control for MSA level variation in the extent of the road network, but unlike actual lane kilometers of highways, are exogenous in demand and supply equations. Using these proxy variables, our supply equation becomes

$$\ln(AC_i) \quad = \quad B_0 + B_1 \ln(Q_i) + B_2 \ln(Z_i) + B_3 X_i + \mu_i. \tag{10}$$

Using the equilibrium condition, $P_i = AC_i$, these equations lead to the estimating equations,

$$\begin{aligned} \ln(Q_i) &= b_0 + b_1 X_i + b_2 Z_i + \eta_i, \\ \ln(P_i) &= a_0 + \rho_Q^P \widehat{\ln(Q_i)} + a_2 X_i + \phi_i. \end{aligned} \tag{11}$$

We note that this is the textbook example of a simultaneous equations estimation (see for example Wooldridge, 2001) and identification of ρ_Q^P depends upon satisfying the exclusion restriction that, conditional on control variables, the instruments shift supply but not demand.

To estimate the demand function for VKT we use the 1995 and 2001 waves of the National Personal Transportation Survey (NPTS).[13] The NPTS actually consists of four surveys.[14] The 'household survey' provides categorical variables describing the age, race, education, and income of the household head or the principal respondent. The 'vehicle survey' provides a detailed description of each household motor vehicle including the survey respondents' report of how many kilometers it was driven in the past twelve months. We use this information to construct an estimate of total VKT for the household during the survey year. This information is reported in the top section of table 5. Surprisingly, these data show that driving distances per person, household, and vehicle all declined between 1995 and 2001. The 'person survey' describes travel behavior for each household member on a typical travel day. From this, we construct household mean commute distance, time and speed for household members who drive to work. Table 5 shows that mean commute distance decreased from 20.4 km in 1995 to 19.4 in 2001. This decrease in distance resulted in a small decrease in mean commute times despite a decline in speed. Finally, the 'travel day' survey collects detailed information about each trip taken by each household member on a randomly selected travel day. These data allow the calculation of household person-kilometers of vehicle travel, along with the person-minutes required to accomplish this travel, and the average speed of this travel. Table 5 shows that total daily household person-kilometers of travel was approximately

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[13] We make use of the confidential geocode information which allows all respondents to be assigned to MSAs. The public use data only reveals respondents's MSAs for respondents residing in large MSAs. We do not use earlier waves of the NPTS because they cannot be geocoded. This allows us to focus on the VKT elasticity of the time cost of travel. In section 6, we consider other travel costs and show that they do not affect the estimation of ρ_Q^P.

[14] It is worth noting that the NPTS survey protocol requires a phone call, a house visit, and that respondents keep a travel diary. Thus it should be regarded as accurate relative to other sources self-reported travel data. The 2000 US census provides an alternative source of information regarding commute times. This information is reported for a sample of the population using 12 time-bands. A comparison between 2000 census and 2001 NPTS data of mean commute times across 227 MSAs yields a raw correlation of 0.63. This correlation is 0.85 when considering only MSAs with population above 1 million. Means computed from the NPTS appear more noisy. Regressing log census mean commute times for all commuters (including those using public transportation) against mean NPTS car commute times yields a coefficient of 1.05 in a regression without constant.

Table 5: Summary statistics for our main NPTS variables (averaged over individuals or HH, means and standard deviations between brackets) and HMPS VKT for corresponding years.

Year:	1995	2001
NPTS vehicle survey		
Mean vehicle km (person)	12,436 (7,737)	12,203 (8,398)
Mean vehicle km (HH)	32,546 (19,672)	30,352 (20,198)
Mean vehicle km (vehicle)	19,560 (9,355)	17,573 (9,030)
NPTS person survey		
Distance to work (km)	20.4 (21.6)	19.4 (20.2)
Minutes drive to work	22.4 (17.3)	21.3 (16.3)
Speed to work	50.9 (21.1)	49.6 (22.1)
NPTS trip survey		
Total HH km	134.8 (119.9)	134.5 (112.0)
Total HH minutes	147.7 (88.7)	160.9 (90.7)
Mean HH km/h	48.4 (12.2)	43.9 (15.1)
Total HMPS VKT		
Interstate Highways ('000 km)	2,876,074	3,484,750
Major Urban Roads ('000 km)	5,530,845	6,624,656
Number MSAs	228	228

constant over the study period, but that the time required to accomplish this travel increased from 147.7 minutes to 160.9 minutes and speed decreased from 48.4 to 43.9 km/h.

The descriptive statistics in table 5 point at stability or a small decline in VKT per household between 1995 and 2001. For the same period, the HPMS indicates increases of around 20% for VKT, as reported at the bottom of table 5. It is natural to wonder whether these two findings are contradictory. To see that they are not, note that the NPTS and the HPMS report different measures of VKT.[15] The NPTS reports a per household measure of VKT on all roads. On the other hand, the HPMS reports aggregate VKT on interstates and major urban roads within MSAs. Thus, the HPMS looks at a different set of roads than the NPTS and the 2001-1995 difference reflects changes in commercial traffic and number of households, in addition to changes in VKT per household.

We now use the NPTS to estimate our demand system (11) and test whether, as implied by the

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[15] We rule out sampling errors. NPTS data sample a large number of households, are broadly acknowledged to be of high quality, and their correlation with census data is also high as mentioned above. Schipper and Moorhead (2000) also provide evidence that reported VKT in the NPTS is highly consistent with odometer VKT from the 1994 Residential Transportation Energy Consumption Survey. As for the HPMS, it is carefully scrutinized by the Bureau of Transportation Statistics which uses it as the basis of its Transportation Statistics Annual Report.

Table 6: Time cost of driving as a function of VKT, pooled regressions.

	[1] OLS	[2] OLS	[3] OLS	[4] TSLS	[5] OLS	[6] OLS	[7] OLS	[8] TSLS
All interstate highways.								
Dependent variable:	ln(hours per km) for commutes				ln(hours per km) for all household driving			
ln(IH VKT)	0.011 (0.01)	-0.056^a (0.01)	-0.051^a (0.01)	-0.060^a (0.02)	0.0062 (0.01)	-0.032^a (0.01)	-0.027^b (0.01)	-0.064^b (0.03)
Personal char.	Y	Y	Y	Y	Y	Y	Y	Y
ln current pop.		Y	Y	Y		Y	Y	Y
Geography		Y	Y	Y		Y	Y	Y
Census div.		Y	Y	Y		Y	Y	Y
Hist. pop.			Y	Y			Y	Y
Observations	46321	46321	46321	46321	19016	19016	19016	19016
R^2	0.04	0.04	0.05	-	0.11	0.12	0.12	-
Overid.				0.11				0.19
First stage Stat.				12.5				11.9

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 235 MSAs represented in each regression. Instruments are log 1835 exploration routes, log 1898 railroads, and log 1947 planned interstates in columns 4 and 8. *a*, *b*, *c*: significant at 1%, 5%, 10%.

fundamental law of road congestion, the demand for VKT is perfectly elastic. In table 6 we pool the 1995 and 2001 NPTS and use 'hours per commute kilometer', the unit time cost of commuting, as our dependent variable for columns 1 through 4. This variable is based on the 'personal' section of the NPTS which asks for commute time and distance. The dependent variable of interest is lane kilometers of interstate highways.

In the first three columns, we ignore the simultaneous determination of price and quantity and regress price on quantity with various other controls using OLS. This shows that equilibrium time cost of commuting is weakly responsive to changes in the quantity supplied of interstate lane kilometers. In column 4 we estimate the two equation model of (11) in order to isolate the slope of the demand function. The estimated demand elasticity is close to zero at -0.06 and, as in columns 1-3, is precisely estimated.

Columns 5 through 8 of table 6 replicate the same regressions using a different dependent variable. The time cost of travel is measured using the 'hours per kilometer of daily driving' calculated from the travel day section of the NPTS. The OLS estimates of the demand elasticities are marginally lower and the TSLS estimate is similar to that of column 4.

As a further robustness check, we replicate these OLS regressions for other types of roads. Our instruments are not strong enough to allow us to replicate IV results for these other types of roads. We obtain very similar OLS results, which are reported in appendix table 8

In sum the data support the hypothesis that the demand for VKT is highly elastic. These results provide independent confirmation of our main result since, given constant returns to scale in the cost of VKT, a perfectly elastic demand for VKT is an implication the fundamental law of road congestion.[16] This conclusion is also of intrinsic interest.

Convergence of AADT levels

The fundamental law of road congestion requires that each MSA have an intrinsic natural level of traffic conditional on lane kilometers of roadway. An implication of this is that a deviation from this natural level ought to be followed by a return to it. Traffic flows should exhibit convergence to this natural level.

The raw data suggests that such convergence may occur. From 1980 to 2000 the cross-MSA standard deviation of all interstate AADT decreases from 1.40 to 1.28. To investigate the possibility of convergence more carefully, table 7 presents the results of 'AADT growth regressions' in which we pool first differences in interstate AADT for 1990 and 2000 and regress them on initial interstate AADT levels.

In the first five columns of panel A we see that the relationship between initial levels and changes in interstate AADT is negative in the cross-section, even as we add an exhaustive set of controls. In column 6 we see that mean reversion persists if we include an MSA fixed effect and consider only time series variation.[17] In column 7 we account for the possibility of an endogenous relationship between changes in AADT and changes in population by instrumenting for the latter using our population change instrument described above. This IV estimate shows mean reversion similar to what we see in the OLS regressions.

In appendix table 9 (in a separate appendix), we replicate these regressions for corresponding measures of AADT for Interstates Highways in urbanized areas, non urban interstates, and major urban roads and find evidence of convergence for these roads as well.

Traffic and transit

The fundamental law of road congestion requires that new road capacity be met with a proportional increase in driving. A corollary is that if we were to somehow remove a subset of a city's drivers from a city's roads, then others would take their place. We can think of public transit

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[16] This high elasticity of the demand for VKT is consistent with the findings on road charging. See for instance Leape (2006) on the London congestion charge.

[17] The much higher coefficient obtained in this regression is reminiscent of results in GDP growth regressions and might be explained by the greater importance of measurement error for differences than for levels.

Table 7: Convergence in daily traffic.

	[1]	[2]	[3]	[4]	[5]	[6]
	OLS	OLS	OLS	OLS	OLS, FE	TSLS
Dependent variable: Change in ln daily traffic (AADT) for interstate highways, entire MSAs.						
Initial ln IH AADT level	-0.11^{a}	-0.12^{a}	-0.17^{a}	-0.22^{a}	-0.98^{a}	-0.17^{a}
	(0.02)	(0.02)	(0.02)	(0.03)	(0.05)	(0.02)
Δ ln(pop.)		0.38^{a}	0.48^{a}	0.29^{b}		0.69^{b}
		(0.10)	(0.11)	(0.14)		(0.31)
Geography			Y	Y		Y
Census div.			Y	Y		Y
Initial Share Manuf.				Y		Y
Hist. pop.				Y		
Socio-econ. char.				Y		
R^2	0.26	0.32	0.39	0.44	0.82	-
First stage Stat.						47.6

All regressions include decade effects. Robust standard errors in parentheses (clustered by MSA).
456 observations corresponding to 228 MSAs for each regression. *a*, *b*, *c*: significant at 1%, 5%, 10%.
Instrument for Δ ln(pop.) is expected population growth based on initial composition of economic activity.

in this way. Public transit serves to free up road capacity by taking drivers off the roads and putting them in buses or trains. It follows that an implication of the fundamental law is that the provision of public transit should not affect the overall level of VKT in a city. We now investigate this proposition.

To measure an MSA's stock of public transit, we use MSA level data on public transit. These data are based on the Section 15 annual reports, and measure public transportation as the daily average peak service of large buses in 1984, 1994, and 2004. We note that these data do not allow us to investigate other forms of public transportation, such as light rail, independently of buses.[18]

Since we expect that the stock of public transit in an MSA may depend in part on how congested is the road network, we are concerned that our measure of public transit will be endogenous in a regression to explain MSA interstate VKT. To deal with this issue, we again resort to instrumental variables estimation. In addition to the 1947 highway plan and 1898 railroad kilometers, we follow Duranton and Turner (2008) and use the MSA share of democratic vote in the 1972 presidential election as an instrument in this estimation.

The 1972 US presidential election between Richard Nixon and George McGovern was fought on the Vietnam War and McGovern's very progressive social agenda. It ended with Nixon's landslide victory. Places where McGovern did well are also arguably places which elected local officials with a strong social agenda. Importantly, this election also took place shortly after the 1970 Urban Mass

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[18] There are too few MSAs with light rail to permit informative cross-sectional analysis. Our data indicate that there are only 11 MSAs with any light rail at all in 1984, and of these only 6 had more than 100 rail cars. The situation is only marginally better in 1994 when 21 MSAs had light rail or commuter rail service and 7 had more than 100 cars. We have experimented with an index that sums large buses and rail cars in the regression performed below, and found no qualitative change in our results.

Transportation Act and it only briefly predates the first oil shock and the 1974 National Mass Transportation Act that followed. While total federal support for public transportation was less than 5 billion dollars (in 2003 dollars) for the entire decade starting in 1960, the 1970 act appropriated nearly 15 billion dollars and the 1974 act appropriated 44 billion dollars. Similar levels of funding persist to the time of this writing (see Weiner, 1997, Hess and Lombardi, 2005, for a history of US public transportation). More generally, during the 1970s public transit expanded and evolved from a private fare-based industry to a quasi-public sector activity sustained by significant subsidies.

In order for a 1972 election to predict 1984 levels of public transit infrastructure, public transit funding must be persistent. In fact, the 'stickiness' of public transit provision is widely observed (Gomez-Ibanez, 1996) and is confirmed in our data. The Spearman rank correlation of bus counts between 1984 and 2004 is 0.90. Our data also suggest that MSAs which voted heavily for McGovern in 1972 made a greater effort to develop public transit in the 1970s, and these high levels of public transit persisted through our study period. Furthermore, the raw data confirms the relevance of our instrument. The pairwise correlation between log 1984 buses and 1972 democratic vote is 0.34. This partial correlation is robust to adding controls for geography and past population. In a nutshell, the 1972 share of democratic vote is a good predictor of the 1984 MSA provision of buses which then grew proportionately to population.

The argument for the exogeneity of the 1972 democratic vote is less strong than that for the road instruments.[19] Nonetheless, a good argument can be made that funding for public transportation in American cities in the early 1970s was a response to contemporaneous social needs. More specifically, the provision of buses at this time did not seek to accommodate traffic congestion during the 1983-2003 period.

Two facts strengthen the case for our empirical strategy. First, as we show below, the results for public transportation are robust and stable as we change specifications. Second, when it is possible to conduct over identification tests, our results always pass these tests.

Regressions in table 8 are similar to regressions in tables 2 and 4 except that we also include the

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[19] In particular, it is possible that a high share democratic vote in 1972 was associated with a variety of other policies and local characteristics that affected subsequent VKT. Since we control for 1980 population (and thus implicitly for growth between 1970 and 1980), we would need these policies to have long-lasting effects and not be reflected in population growth. In this respect, Glaeser, Scheinkman, and Schleifer (1995) find very weak or no association between a number of urban policies (though not public transport) and urban growth between 1960 and 1990. In addition, recent work by Ferreira and Gyourko (2009) could find no evidence of any partisan effect with respect to the allocation of municipal expenditure.

Table 8: VKT as a function of lane kilometers and buses, pooled regressions.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
	OLS	OLS	OLS	OLS	OLS	OLS	LIML	LIML	LIML	LIML
Panel A. Dependent variable: ln VKT for interstate highways, entire MSAs										
ln(IH lane km)	1.07^{a}	0.82^{a}	0.86^{a}	0.86^{a}	1.06^{a}	1.06^{a}	1.38^{a}	0.96^{a}	1.09^{a}	1.18^{a}
	(0.04)	(0.05)	(0.05)	(0.04)	(0.05)	(0.05)	(0.08)	(0.10)	(0.13)	(0.17)
ln(bus)	0.14^{a}	-0.023	0.026	0.039^{b}	0.021^{b}	0.012^{c}	-0.035	-0.081^{c}	0.12	0.21
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.05)	(0.05)	(0.10)	(0.14)
ln(pop.)		0.51^{a}	0.40^{a}	0.26^{b}		0.32^{a}		0.50^{a}	0.079	-0.15
		(0.05)	(0.05)	(0.12)		(0.10)		(0.12)	(0.21)	(0.27)
Geography			Y	Y					Y	Y
Census div.			Y	Y					Y	Y
Socio-econ. char.				Y						Y
Hist. pop.				Y						Y
MSA fixed effects					Y	Y				
R^2	0.90	0.94	0.95	0.96	0.94	0.94	-	-	-	-
Overid.							0.90	0.46	0.47	0.38
First stage Stat.							23.3	21.1	9.53	5.68
Panel B. Dependent variable: ln VKT for interstate highways, urbanized areas within MSAs										
ln(IHU lane km)	1.14^{a}	0.98^{a}	1.00^{a}	1.01^{a}	0.99^{a}	0.99^{a}	1.32^{a}	1.10^{a}	1.28^{a}	1.29^{a}
	(0.03)	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.06)	(0.14)	(0.19)	(0.20)
ln(bus)	0.086^{a}	-0.0049	0.038^{c}	0.049^{a}	0.0083	0.0026	-0.056	-0.078^{c}	0.059	0.089
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.04)	(0.05)	(0.08)	(0.09)
ln(pop.)		0.36^{a}	0.26^{a}	0.18		0.21^{b}		0.34^{c}	-0.083	-0.13
		(0.04)	(0.05)	(0.13)		(0.09)		(0.18)	(0.27)	(0.28)
R^2	0.96	0.97	0.97	0.98	0.95	0.95	-	-	-	-
Overid.							0.73	0.33	0.94	0.85
First stage Stat.							23.4	6.29	5.24	2.94

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 684 observations corresponding to 228 MSAs for each regression in panel A and 576 (192 MSAs) in panel B. Instruments for buses and lane kilometers are ln 1898 railroads, ln 1947 planned interstates, and 1972 presidential election share of democratic vote. *a*, *b*, *c*: significant at 1%, 5%, 10%.

log count of large buses in an MSA as an explanatory variable. In columns 1 through 6 we present OLS regressions while in columns 7 through 10 we report LIML regressions (rather than TSLS since our set of instruments is sometimes marginally weak). In panel A of table 8 our dependent variable is log VKT for all interstates. As in results reported earlier, the lane kilometer elasticity of VKT is close to one in all specifications. The second row of panel A gives our estimates of the bus elasticity of VKT. These estimates are consistently small, are precisely estimated, do not have a consistent sign, and are often statistically indistinguishable from zero. Panel B of table 8 uses MSA VKT on urbanized area interstate highways as its dependent variable and its corresponding measure of lane kilometers as its measure of roads. While the resulting roadway elasticity estimates are somewhat larger and less precisely estimated, they are qualitatively similar to the results of panel A. For public transit as measured by the count of large buses in an MSA, the conclusion is the same as in panel A: the provision of buses does not affect total VKT in the MSA.

To check the robustness of this finding, appendix table 10 (in a separate appendix) repeats some of the regressions of table 8 for each of our three cross-sections. The resulting estimates of the bus elasticity of vkt are qualitatively unchanged. As a further check, appendix table 11 repeats many of the regressions of table 8 using measures on non-urbanized interstate lane kilometers and vkt and urbanized area major road kilometers and vkt. Finally appendix table 12 repeats the regressions of table 8 using a broader measure of transit adding all train cars to our count of buses. The resulting elasticity estimates of these two tables also support the conclusion that public transit does not affect traffic levels.

Finally, we note that the finding that public transit does not reduce traffic levels should be of independent interest to policy makers.

5. Where does all the vkt come from?

Our data show that building roads elicits a large increase in vkt on those roads. We now turn our attention to understanding where all the extra vkt comes from. In particular, we consider four possible sources of demand for vkt: changes in individual behavior; the migration of people and economic activity, increases in the commercial transportation sector, and diversion of traffic from other roads.

Commercial vkt

To investigate the relationship between changes in the road network and changes in truck vkt we first use the hpms Sample data's reports of the daily share of single unit and combination trucks using each road segment on an average day. With our other data, this allows us to calculate truck vkt for all roads in our sample. With these measures of truck vkt in hand, we replicate our earlier analysis of all vkt for truck vkt.

Table 9 reports these results. In panel a our dependent variable is all interstate highway truck vkt and the explanatory variable of interest is lane kilometers of interstate highways. In columns 1 through 5, we report the results of ols estimates. In columns 6, 7 and 8 we include an msa fixed effect and identify the effect of highways on truck vkt using only time series variation. In columns 9 and 10 we report tsls where we use our three historical variables to instrument for contemporaneous lane kilometers. In every case, our estimate of the highway elasticity of truck vkt is above one and is estimated precisely. While the ols and fixed effect estimates are generally

Table 9: Truck VKT as a function of lane kilometers, pooled regressions.

	[1] OLS	[2] OLS	[3] OLS	[4] OLS	[5] OLS	[6] OLS	[7] OLS	[8] OLS	[9] TSLS	[10] TSLS
Panel A. Dependent variable: ln Truck VKT for interstate highways, entire MSAs										
ln(IH lane km)	1.30^{a}	1.16^{a}	1.20^{a}	1.25^{a}	1.19^{a}	1.46^{a}	1.48^{a}	1.52^{a}	2.09^{a}	2.32^{a}
	(0.07)	(0.13)	(0.13)	(0.13)	(0.14)	(0.26)	(0.27)	(0.27)	(0.44)	(0.43)
ln(pop.)		0.16^{c}	0.13	0.23^{b}	1.79^{b}		2.14^{b}	2.02^{b}	-0.48	-0.77^{b}
		(0.08)	(0.11)	(0.10)	(0.79)		(0.94)	(0.91)	(0.31)	(0.34)
Geography			Y	Y	Y					Y
Census div.			Y	Y	Y					Y
Socio-econ. char.				Y	Y			Y		
Hist. pop.					Y					
MSA fixed effects						Y	Y	Y		
R^2	0.53	0.54	0.58	0.59	0.61	0.31	0.34	0.34	-	-
Overid.									0.27	0.18
First stage Stat.									16.5	11.8
Panel B. Dependent variable: ln Truck VKT for Major Roads, urbanized areas with MSAs										
ln(MRU lane km)	1.05^{a}	0.58^{a}	0.63^{a}	0.66^{a}	0.63^{a}	0.71^{a}	0.69^{a}	0.69^{a}		
	(0.03)	(0.11)	(0.10)	(0.09)	(0.10)	(0.10)	(0.11)	(0.11)		
ln(pop.)		0.50^{a}	0.46^{a}	0.49^{a}	0.37		1.06^{a}	1.07^{a}		
		(0.11)	(0.10)	(0.10)	(0.22)		(0.18)	(0.18)		
R^2	0.64	0.66	0.69	0.70	0.71	0.23	0.25	0.25		

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 684 observations corresponding to 228 MSAs for each regression in panel A and 576 (192 MSAs) in panel B. Instruments are ln 1835 exploration routes, ln 1898 railroads, and ln 1947 planned interstates.
a, *b*, *c*: significant at 1%, 5%, 10%.

within two standard deviations of one, the IV estimates in columns 9 and 10 are above 2 and are more than two standard deviations from one.

In panel B of table 9 we replicate the OLS estimations of panel A, but measure roadway and truck VKT for major urban roads (but not the TSLS because our instruments are weak). Truck VKT in cities responds less to changes in major roads than does interstate truck traffic to changes in interstates. These results are confirmed in Appendix table 13 which runs separate regressions for each decade.

In all, we find that a 10% increase in interstate highways causes about a 10-20% increase in truck VKT, so that commercial traffic is at least as responsive to road supply as other traffic.

In a separate appendix, we also examine the relationship between roads and employment in traffic intensive activities. We use County Business Patterns data for 1983, 1993, and 2003. These data provide county level information on employment in "Motor freight transportation and warehousing" (SIC 42). Appendix tables 14 and 15 present results of regressions predicting log MSA employment in trucking and warehousing. These regressions show that employment in this sector increases with interstate lane kilometers, that it is more responsive to the supply of non-urbanized area interstate than to the supply of urbanized area interstate, and that it has become more sensitive to changes in the supply of interstate highways over the course of our study period.

Overall, our findings suggest that improvements to highways cause large increases in the use of these routes by long-haul truckers, and that improvements to the local road network cause smaller increases in local commercial traffic.

Individual driving behavior and highways

We now investigate the extent to which individual or household driving behavior changes in response to changes in the extent of an MSA's interstate network. To accomplish this, we look at the relationship between lane kilometers of interstate highway and three different measures of individual and household driving taken from the NPTS.

We estimate two basic equations using our two pooled cross-sections of the NPTS. The first is our city level cross-section estimating equation (2), adjusted to reflect the fact that our unit of observation is now a person or household in a particular city and year. In particular, we estimate,

$$\ln(Q_j^{\text{AR}}) = A_0 + \rho_{R^{\text{IH}}}^{Q^{\text{AR}}} \ln(R_{ij}^{\text{IH}}) + A_1 X_{ij} + \epsilon_j, \tag{12}$$

where Q_j^{AR} denotes VKT on all roads for household (or individual) j and i indexes MSAs. Because of the log specification, the coefficient on lane kilometers is the elasticity of household VKT on all roads with respect to highway lane kilometers. We include as control variables both MSA level characteristics and individual demographic characteristics, and allow for clustering of errors at the MSA level.

Our second equation is the individual or household level analog of our instrumental variables estimating equation (5). Here, our first stage equation predicts interstate kilometers and is identical to the first stage in equation (5), the second stage corresponds to equation (12).

Summary statistics for the NPTS are provided in table 5. Table 10 reports the results of regressions to explain three measures of individual driving using pooled cross-sections from the 1995 and 2001 NPTS. Panel A of the table presents OLS estimates and panel B presents TSLS estimates. In the first three columns our dependent variable is commute kilometers on a typical day for all NPTS individuals who commute. In columns 4 through 6 our dependent variable is total household person vehicle kilometers on a particular travel day. In columns 7 through 9, our dependent variable is total VKT by all household vehicles in the survey year.

With the exception of the regression in column 7, for which there is no measurable relationship between interstate kilometers and household vehicle kilometers, all estimates suggest a positive

Table 10: Individual travel as a function of interstate lane kilometers.

	ln commute distance			**ln HH daily VKT**			**ln HH annual VKT**		
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Panel A (OLS) on interstate highways, entire MSAs.									
ln(IH lane km)	0.086^{a}	0.061^{a}	0.065^{a}	0.036^{a}	0.065^{a}	0.061^{a}	-0.019	0.051^{b}	0.052^{b}
	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
ln(pop.)		0.026	0.066		-0.011	0.10		-0.045^{b}	-0.089
		(0.02)	(0.08)		(0.02)	(0.12)		(0.02)	(0.10)
Geography		Y	Y		Y	Y		Y	Y
Census div.		Y	Y		Y	Y		Y	Y
Hist. pop.			Y			Y			Y
Observations	46321	46321	46321	19016	19016	19016	17865	17865	17865
R^2	0.06	0.07	0.07	0.14	0.14	0.14	0.24	0.25	0.25
Panel B (TSLS) on interstate highways, entire MSAs. Instruments: ln 1898 railroads and ln 1947 planned interstates									
ln(IH lane km)	0.090^{a}	0.094^{a}	0.10^{a}	0.058^{a}	0.15^{c}	0.15^{c}	-0.0040	0.11^{c}	0.13^{b}
	(0.01)	(0.03)	(0.03)	(0.02)	(0.08)	(0.08)	(0.02)	(0.06)	(0.06)
ln(pop.)		-0.00018	0.059		-0.083	0.057		-0.095^{b}	-0.13
		(0.03)	(0.08)		(0.07)	(0.12)		(0.05)	(0.11)
Observations	46321	46321	46321	19016	19016	19016	17865	17865	17865
Overid.	0.11	0.25	0.98	0.11	0.039	0.13	0.69	0.28	0.16
First stage Stat.	54.5	20.2	18.9	68.6	17.1	15.8	66.5	16.2	14.9

All regressions include a constant. Standard errors in parentheses, clustered by MSA.
228 MSAs represented in all regressions. *a*, *b*, *c*: significant at 1%, 5%, 10%.

and statistically significant relationship between the extent of the highway network and individual travel. Our preferred estimates are the TSLS estimates in panel B. These estimates suggests that a 10% increase in the extent of the interstate network causes about a 1% increase in individual driving on all roads. While the NPTS data does not reveal which classes of roads accommodate this increase in driving, in what follows we use the HPMS to explore the diversion of traffic between classes of roads.

Population growth

By reducing the cost of transportation within a city, all else equal, improvements to a city's road network make a city more attractive relative to other cities. Given the high mobility of the US population, this suggests that changes to a city's road network should be met with changes to a city's population. In fact, this conjecture appears to be true, and the extant literature estimates the size of this effect.

Both Michaels (2008) and Chandra and Thompson (2000) provide suggestive evidence. Both papers consider the effect of improvements in access to the interstate system on rural counties in the US. Michaels (2008) finds that an interstate highway in a rural county leads to large increases in retail earnings. Chandra and Thompson (2000) find that improved access to the8 interstate system causes an overall increase in firm earnings. Together, these results show that interstate highways cause increases in the level of local economic activity. To the extent that population levels and overall economic activity are linked, this suggests that improvements to the interstate network lead to population increases.

Duranton and Turner (2008) provide more direct evidence. Duranton and Turner (2008) consider US MSAs between 1980 and 2000, and investigate the way that population growth responds to changes in the road network. Like the current paper, they rely on an early plan of the interstate highway network and 1898 railroad routes as instruments for the modern road network. They find that a 10% increase the extent of the road network causes a 1.3% increase in MSA population over 10 years, and a 2% increase over 20 years.

Diversion from other roads

We measure traffic and lane kilometers for three exclusive classes of roads in each MSA; urbanized area interstates, non-urbanized area interstates, and major urbanized area roads. These data allow direct tests of whether changes to one class of roads affects VKT on the others. In particular, we estimate each of the three following variants of equation (2),

$$\begin{aligned}
\ln(Q_{it}^{\text{IHU}}) &= A_0 + \rho_{R^{\text{IHU}}}^{Q^{\text{IHU}}} \ln(R_{it}^{\text{IHU}}) + \rho_{R^{\text{IHNU}}}^{Q^{\text{IHU}}} \ln(R_{it}^{\text{IHNU}}) + \rho_{R^{\text{MRU}}}^{Q^{\text{IHU}}} \ln(R_{it}^{\text{MRU}}) + A_1 X_{it} + \epsilon_{it} & (13)\\
\ln(Q_{it}^{\text{IHNU}}) &= B_0 + \rho_{R^{\text{IHU}}}^{Q^{\text{IHNU}}} \ln(R_{it}^{\text{IHU}}) + \rho_{R^{\text{IHNU}}}^{Q^{\text{IHNU}}} \ln(R_{it}^{\text{IHNU}}) + \rho_{R^{\text{MRU}}}^{Q^{\text{IHNU}}} \ln(R_{it}^{\text{MRU}}) + B_1 X_{it} + \gamma_{it} & (14)\\
\ln(Q_{it}^{\text{MRU}}) &= C_0 + \rho_{R^{\text{IHU}}}^{Q^{\text{MRU}}} \ln(R_{it}^{\text{IHU}}) + \rho_{R^{\text{IHNU}}}^{Q^{\text{MRU}}} \ln(R_{it}^{\text{IHNU}}) + \rho_{R^{\text{MRU}}}^{Q^{\text{MRU}}} \ln(R_{it}^{\text{MRU}}) + C_1 X_{it} + \nu_{it}. & (15)
\end{aligned}$$

In equation (13), $\rho_{R^{\text{IHNU}}}^{Q^{\text{IHU}}}$ is the urbanized area interstate VKT elasticity of non urbanized area interstate lane kilometers. If, for example, this parameter is -0.1 then a 10% increase in non-urbanized area interstate lane kilometers results in a 1% decrease in urbanized area interstate VKT. Interpretation of other coefficients is similar.

Table 11 reports estimates of equations (13)-(15). In all regressions we pool our three cross-sections of HPMS data and use OLS. Panel A presents estimates of equation (13). In these regressions our dependent variable is urbanized area interstate VKT and the dependent variables of interest are the three measures of lane kilometers. The first five columns exploit cross-sectional variation and from left to right, use progressively more exhaustive lists of controls. In columns 6 through 8 we include an MSA fixed effect and exploit only time series variation. Panels B and C are similar to panel A, but use non-urbanized interstate VKT and major urbanized area road VKT as dependent variables.

Consistent with our earlier results we see that VKT elasticity of own lane kilometers is close to one in all specifications. The largest estimated cross elasticity is 0.22 for the non-urbanized area interstate VKT elasticity of urbanized area major road lane kilometers, in column 1, row 3 of panel B. This estimate is not robust to the addition of controls, and is negative or indistinguishable from zero in other specifications. The estimate of the urbanized area interstate VKT elasticity of urbanized area major road lane kilometers in row 3 column 1 of panel A is similar. Other cross-elasticities are generally quite small. Our preferred regressions are reported in column 5. In this specification, all cross-elasticities are negative with magnitudes no larger than 0.1. In sum, table 11 suggests that, while traffic diversion does occur in response to changes in the road network, the fundamental law of road congestion mainly reflects traffic creation not traffic diversion.

In a separate appendix, we confirm these results in appendix tables 16 and 17. In these tables we replicate the results of table 11 in decade by decade OLS regressions and in first difference regressions.

An accounting exercise

The fundamental law of road congestion requires that changes in the extent of the road network are met with proportional changes in traffic. We have suggested four possible sources for this increase in traffic; changes in trucking and commercial driving, changes in individual or household driving behavior, changes in population, and diversion of traffic. We now consider whether these four sources are sufficient to explain the fundamental law and assess their relative importance.

To begin, consider a 10% increase in the interstate network of an average MSA around 2000. Using our preferred estimate from column 5 of table 4, this increase causes a 10.4% increase in VKT on the interstates of our hypothetical city.

In table 1 we see that in 2003, trucks accounted for 13% of VKT on interstate highways in an average MSA. In table 9, our preferred specification is column 10, where the truck VKT elasticity of interstate highways is about 2.3. This means that a 10% increase in the stock of roads causes about a 23% increase in truck VKT and a 2.9% increase in overall interstate VKT, about 28% of the total increase in VKT caused by our 10% increase in roads. While our preferred elasticity of 2.3 may

Table 11: VKT as a function of lane kilometers for different types of roads, pooled OLS.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A. Dependent variable: ln VKT for interstate highways, urbanized areas within MSAs								
ln(IHU lane km)	1.09^{a}	1.01^{a}	1.04^{a}	1.03^{a}	1.04^{a}	1.00^{a}	1.00^{a}	0.98^{a}
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
ln(IHNU lane km)	-0.026	-0.083^{a}	-0.086^{a}	-0.087^{a}	-0.099^{a}	0.063^{b}	0.059^{c}	0.061^{b}
	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
ln(MRU lane km)	0.22^{a}	-0.13^{b}	-0.12^{b}	-0.12^{b}	-0.100^{b}	-0.042	-0.049	-0.049
	(0.04)	(0.06)	(0.06)	(0.05)	(0.05)	(0.03)	(0.03)	(0.03)
ln(pop.)		Y	Y	Y	Y		Y	Y
Geography			Y	Y	Y			
Census div.			Y	Y	Y			
Socio-econ. char.				Y	Y			Y
Hist. pop.					Y			
MSA fixed effects						Y	Y	Y
R^2	0.96	0.97	0.97	0.98	0.98	0.94	0.94	0.95
Panel B. Dependent variable: ln VKT for interstate highways, outside urbanized areas within MSAs								
ln(IHU lane km)	0.032	-0.049	-0.030	-0.030	-0.013	0.014	0.0057	-0.0057
	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
ln(IHNU lane km)	0.87^{a}	0.81^{a}	0.84^{a}	0.85^{a}	0.83^{a}	0.97^{a}	0.96^{a}	0.96^{a}
	(0.04)	(0.03)	(0.03)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
ln(MRU lane km)	0.22^{a}	-0.14^{b}	-0.053	-0.046	-0.013	-0.012	-0.021	-0.020
	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.03)	(0.03)	(0.03)
R^2	0.85	0.88	0.92	0.92	0.93	0.89	0.89	0.90
Panel C. Dependent variable: ln VKT for Major Roads, urbanized areas within MSAs								
ln(IHU lane km)	0.015	-0.049^{a}	-0.049^{a}	-0.057^{a}	-0.048^{a}	-0.016	-0.026	-0.034
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
ln(IHNU lane km)	0.042^{b}	-0.0038	0.00063	-0.0044	-0.0042	0.029	0.022	0.022
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
ln(MRU lane km)	1.09^{a}	0.81^{a}	0.82^{a}	0.81^{a}	0.82^{a}	0.85^{a}	0.84^{a}	0.84^{a}
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
R^2	0.97	0.98	0.99	0.99	0.99	0.93	0.94	0.94

All regressions include a constant and year effects. Robust standard errors clustered by MSA in parentheses. 572 observations corresponding to 192 MSAs for each regression. *a*, *b*, *c*: significant at 1%, 5%, 10%.

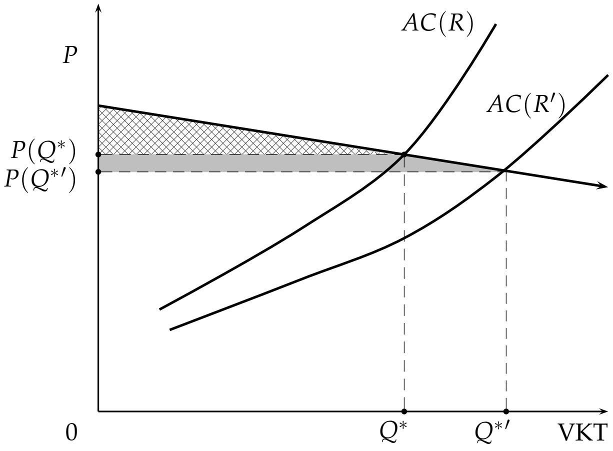
seem high, the average of all estimates in panel A of table 9 is 1.5. This value would imply that trucks represent 18% of the total increase in VKT. Therefore, we estimate that trucks account for between 18 and 28% of the total increase in interstate VKT that results from our hypothetical 10% increase in interstate lane kilometers.

For migration, taking the preferred estimate from Duranton and Turner (2008), our 10% increase in the interstate network causes about a 2% increase in population. From column 5 of table 4, the MSA population elasticity of interstate VKT is 0.23. Together, these two elasticities suggest that a 10% increase in population results in about a 0.5% increase interstate VKT, about 5% of the total increase. This elasticity of 0.23 is estimated in a regression that also controls for decennial population levels between 1920 and 1970. Because decennial population levels are highly correlated, this may understate the effect of population on VKT. Appendix table 6 which controls for the endogeneity of population in first difference reports higher estimates. Our favored estimate in column 5 is 0.76. This alternative value implies that population growth represents 15% the total effect of an extension in interstate lane kilometers. Therefore, we estimate that migration accounts for between 5 and 15% of the total increase in interstate VKT that results from our hypothetical 10% increase in interstate lane kilometers.

Turning to substitution across roads, we suppose that the 10% increase in our MSA's interstate lane kilometers network is accomplished by increasing both urbanized and non-urbanized interstates by 10%. Since we are considering increases to both classes of interstate highways, we need only be concerned with diversion of traffic from major urbanized area roads. This is estimated in panel C of table 11. Our preferred specification is in column 5. In rows 1 and 2, we see that a 10% increase in urbanized and non-urbanized interstate causes a decrease in major urban road VKT of 0.48% and 0.04%, respectively. That is, our 10% increase in interstate lane kilometers diverts 0.52% of traffic from major urban roads. Using the levels of VKT for major urban and all interstates given in table 1 allows us to calculate that this diversion amounts to about a 1% increase in interstate VKT, or about 10% of the total effect of our hypothetical 10% extension. Because many estimates in table 11 (or in appendix tables 16 and 17) indicate no substitution from major urban roads towards interstates, we cannot rule out the absence of a substitution effect. Therefore, we estimate that the diversion of traffic from other classes of roads accounts for between 0 and 10% of the total increase in interstate VKT that results from our hypothetical 10% increase in interstate lane kilometers.

Calculating the contribution of changes to household behavior is more difficult. Table 10 estimates the effect of interstate lane kilometers on individual driving behavior. Our preferred estimates of this elasticity is 0.13 in column 9 of panel B (and is very close to the corresponding estimate for alternative measures of VKT in columns 3 and 6). A 10% increase in interstate lane kilometers causes a 1.3% increase in household annual VKT. Unfortunately, our data do not allow us to apportion household driving to different road networks. A first possibility is to assume that this 1.3% increase in driving is proportional to current driving across all road networks. Since households represent 87% of interstate VKT, this 1.3% increase represents an increase in interstate VKT of 1.1% or 11% of the total increase in interstate VKT caused by a 10% increase in lane kilometers. This is arguably an unrealistic lower bound. Alternately, suppose that the 1.3% increase in household driving takes place only on interstates (recall that we earlier reported that about 24% of VKT takes place on interstates). In this case, the increase in interstate VKT would

Figure 5: Second best surplus from change in VKT.



account for 4.8% of the total change in VKT or 46% of the effect of our expansion in lane miles. This constitutes an upper-bound. Therefore, we estimate that increases in household driving account for between 11 and 46% of the total increase in interstate VKT that results from our hypothetical 10% increase in interstate lane kilometers.

To sum up, of four possible sources for the new traffic following an increase in lane kilometers of interstates, changes to individual behavior and changes in commercial driving are the most important. Migration and traffic diversion are significantly less important. We also note that if we take the upper bound for the shares of all four sources we account for the entire increase in VKT.

6. Welfare calculation

Highway provision and welfare

That expansions of highways are met with large increases in VKT is sometimes used to argue that the social value of new road capacity is low (Cervero, 2002, reports several such claims). To understand why this argument is false, it is helpful to return to our simple model of the demand and supply of traffic.

Figure 5 describes demand and supply for VKT, and is similar to figure 1, except that it also represents the welfare gain for VKT associated with an increase in lane kilometers from R to $R^{'}$. Note first that the total cost of supplying Q with R is simply the average cost times quantity,

$AC(R) \times Q^*$.[20] In figure 3, this is the area of the rectangle whose northeast corner is the equilibrium point and whose southwest corner is the origin. The consumers' surplus associated with Q^* is the area under the demand curve and above average cost between 0 and Q^*. It is equal to the social surplus and it is represented by the hatched triangle in the figure. If we increase lane kilometers to $R^{'}$ we see that the resulting marginal change to this surplus is given by the area of the shaded quadrilateral in figure 3.

We note three issues before proceeding. First and because the equilibrium is inefficient, we compute the welfare change associated with an increase in the stock of highways given free access to these highways. Estimating first-best VKT for given R is beyond the reach of our data because such an estimation requires an estimation of the marginal cost function for VKT. Moreover, given that comprehensive congestion pricing is, optimistically, still some distance in the future, the calculation of such an optimum is of little practical value to policy makers. Second, we consider a small increase in lane kilometers in one MSA. We assume it does not affect travel conditions in other MSAs. Third, this calculation ignores any cost or benefit effect not reflected in the cost curve. Possible examples include pollution, carbon emissions, greater productivity or improved land access.[21] A full welfare calculation taking into account general equilibrium and external effects is beyond the scope of this paper and would require additional detailed land market information in the tradition of Mohring (1961). Here, we focus only on travel issues which are often the key justification put forward in favor of road investments.

Suppose that in figure 3, $R^{'}$ is one percent larger than R. After dropping the * superscript for equilibrium values, it follows that $Q^{'} \approx (1 + \rho_R^Q/100)I$. Considering only the cost of driving that varies with VKT, we have $P^{'} \approx \left(1 + \rho_R^P/100\right) P$ where ρ_R^P is the elasticity of the cost of VKT with respect to lane kilometers. Hence the change in surplus, ΔW, associated with a 1% increase in the stock of lane kilometers is,

$$\begin{aligned} \Delta W &\approx \tfrac{1}{2}\left(Q + Q^{'}\right) \times \left(P - P^{'}\right) \\ &= -\left(1 + \tfrac{\rho_R^Q}{200}\right) Q \times \tfrac{1}{100}\,\rho_R^P\, P. \end{aligned} \tag{16}$$

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[20] We ignore the cost of building and maintaining roads for the time being.

[21] To understand this last point, consider a central city and a close suburb, both with a unit supply of residences and hosting half the residents each. Assume the highway between central city and the close suburb that all suburban residents use is doubled in length to reach a remote suburb. Each location then hosts a third of the residents and this leads to a doubling of VKT. However the utility of residents increases since land consumption per capita is now 50% larger. We are grateful to Edward Glaeser for this point.

We note that $\rho^P_R = \rho^P_Q \times \rho^Q_R$, where ρ^P_Q is the VKT elasticity of the price of VKT, that is, the inverse of the price elasticity. Using this elasticity decomposition, dividing by the amount of new lane kilometers, $R/100$, and rearranging gives the marginal welfare gain associated with an additional lane kilometer. Using the superindex IH to denote interstate highways, we have

$$\Delta w^{\text{IH}} \approx -\rho^{P^{\text{IH}}}_{Q^{\text{IH}}}\,\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}\,P^{\text{IH}}\left(1+\frac{\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}}{200}\right)\frac{Q^{\text{IH}}}{R^{\text{IH}}}. \tag{17}$$

Because of substitution between highways and other roads, we expect an increase in highway lane kilometers to affect also the cost of driving on other roads. Similar arguments lead us to write the expression for the marginal welfare change for other roads corresponding to (17) as,

$$\Delta w^{\text{OR}} \approx -\rho^{P^{\text{OR}}}_{Q^{\text{IH}}}\,\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}\,P^{\text{OR}}\left(1+\frac{\rho^{Q^{\text{OR}}}_{R^{\text{IH}}}}{200}\right)\frac{Q^{\text{OR}}}{R^{\text{IH}}}. \tag{18}$$

In this expression we use OR to superindex quantities for other roads so that Q^{OR} is VKT on other roads, P^{OR} its price, $\rho^{P^{\text{OR}}}_{Q^{\text{IH}}}$ the highway VKT elasticity of the price of driving on other roads, and $\rho^{Q^{\text{OR}}}_{R^{\text{IH}}}$, the highway elasticity of other road VKT.

Finally, the total marginal welfare gain from an additional lane kilometer of highway is $\Delta w = \Delta w^{\text{IH}} + \Delta w^{\text{OR}}$.

A complete calculation of all the terms in (17) and (18) requires data well beyond what we have available. Nonetheless, we can compute an upper bound for Δw. First, as shown by table 11 an increase in highway lane kilometers has a stronger effect on highway VKT than on VKT on other roads so that $\rho^{Q^{\text{IH}}}_{R^{\text{IH}}} > \rho^{Q^{\text{OR}}}_{R^{\text{IH}}}$. Second, according to the US FHWA (2005), VKT on interstates represents about one quarter of total VKT so that $Q^{\text{OR}} \approx 3\,Q^{\text{IH}}$. Under these assumptions, it is simple to show that:

$$\Delta w < -\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}\frac{Q^{\text{IH}}}{R^{\text{IH}}}\left(1+\frac{\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}}{200}\right)\left(\rho^{P^{\text{IH}}}_{Q^{\text{IH}}}\,P^{\text{IH}} + 3\,\rho^{P^{\text{OR}}}_{Q^{\text{IH}}}\,P^{\text{OR}}\right). \tag{19}$$

Third, we note that our information for the time cost of driving is from the NPTS. It is for all roads and cannot distinguish between highways and other roads. Thus, to evaluate equation (19) we must transform it so that all terms involving the cost of travel are evaluated over all roads. This is possible under the mild assumptions described below.

With about three times as much traffic on other roads as on highways, the price of driving on all roads can be approximated by $P^{\text{AR}} \approx [3\,P^{\text{OR}} + P^{\text{IH}}]/4$ and its corresponding highway VKT elasticity is $\rho^{P^{\text{AR}}}_{Q^{\text{IH}}} \approx \left(3\rho^{P^{\text{OR}}}_{Q^{\text{IH}}} + \rho^{P^{\text{IH}}}_{Q^{\text{IH}}}\right)/4$, where the superindex 'AR' is used for quantities that apply to all roads. Fourth, we expect the cost of driving to be higher on other roads than on interstates,

$P^{\text{OR}} > P^{\text{IH}}$. Under reasonable demand conditions, we also expect the highway VKT elasticity of the cost of highway driving to be larger than the highway VKT elasticity of the cost of driving on other roads, $-\rho^{P^{\text{IH}}}_{Q^{\text{IH}}} > -\rho^{P^{\text{OR}}}_{Q^{\text{IH}}}$. Under these assumptions, a simple argument shows that $4\,(-\rho^{P^{\text{AR}}}_{Q^{\text{IH}}})P^{\text{AR}} > (-\rho^{P^{\text{IH}}}_{Q^{\text{IH}}})P^{\text{IH}} + 3\,(-\rho^{P^{\text{OR}}}_{Q^{\text{IH}}})P^{\text{OR}}$. It follows immediately that,

$$\Delta w < \rho^{Q^{\text{IH}}}_{R^{\text{IH}}} \frac{4\,Q^{\text{IH}}}{R^{\text{IH}}} \left(1 + \frac{\rho^{Q^{\text{IH}}}_{R^{\text{IH}}}}{200}\right) P^{\text{AR}} \left(-\rho^{P^{\text{AR}}}_{Q^{\text{IH}}}\right). \tag{20}$$

In this expression, $Q^{\text{IH}}/R^{\text{IH}}$ is interstate highway AADT which can be read directly from the HPMS data for each MSA. Using the fundamental law of highway congestion, we have $\rho^{Q^{\text{IH}}}_{R^{\text{IH}}} = 1$. This implies:

$$\Delta w < 4.02\text{AADT}^{\text{IH}} \times P^{\text{AR}} \left(-\rho^{P^{\text{AR}}}_{Q^{\text{IH}}}\right). \tag{21}$$

Time in vehicle

To estimate P^{AR} and its associated highway VKT elasticity, we consider both the time cost of driving and the cost of operating a vehicle. Since the elasticities are likely to differ, we consider both components separately:

$$\rho^{P^{\text{AR}}}_{Q^{\text{IH}}}\, P^{\text{AR}} \equiv \rho^{TC^{\text{AR}}}_{Q^{\text{IH}}}\, TC^{\text{AR}} + \rho^{VOC^{\text{AR}}}_{Q^{\text{IH}}}\, VOC^{\text{AR}}, \tag{22}$$

where TC denotes time-in-vehicle cost and VOC denotes vehicle operating costs.

Measuring time-in-vehicle costs TC^{AR} is relatively straightforward. Using the NPTS trip data, we compute time per kilometer by inverting our estimates of trip speed for each MSA.[22] Census data for mean MSA incomes in 2000 allows us to calculate an MSA hourly income assuming 2500 hours per year.[23] We adjust this wage by a 'wage factor' to take into account that workers may not value time in vehicle in the same way as time at work. The product of hours per kilometer by hourly wage adjusted by a wage factor is our measure of TC^{AR}. According to Small and Verhoef (2007), the standard approach in transportation studies is to value the time cost of commuting at half the wage. We follow this approach. As an illustration and taking median MSA values, 0.023 hour per kilometer valued at a 2000 hourly wage of \$ 20.20 adjusted by a factor of 50% (and inflation) implies a time cost of \$ 0.26 per km in 2008 dollar.

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[22] Focusing on regular commutes rather than all trips on a given day leads to a slightly lower cost per kilometer. We retain the higher number.

[23] The American Time Use Survey reports around 1260 hours of work per person above the age of 15 annually. With 2.66 people per household and slightly less than 80% of the population above the age of 15, this implies around 2,630 hours of work per household annually. We take 2,500 to remain conservative. This yields wages about 15% higher in real terms than wages from the US Bureau of Labor Statistics as used by Ng and Small (2008).

The elasticity $\rho_{Q^{\text{IH}}}^{TC^{\text{AR}}}$ is what is estimated in table 6.[24] The first four columns of panel A of the table estimate $\rho_{Q^{\text{IH}}}^{TC^{\text{AR}}}$ using commutes times per kilometer for TC^{AR} and VKT for MSA interstates. The estimates are between -0.05 and -0.06 when we control for city characteristics. Using measures of TC^{AR} from all household driving leads to slightly lower OLS estimates and a similar TSLS estimate. Given these results, we use -0.06 as baseline value for $\rho_{Q^{\text{IH}}}^{TC^{\text{AR}}}$. Because we have less confidence in this elasticity than in our unit value for $\rho_{R^{\text{IH}}}^{Q^{\text{IH}}}$ and because it plays an important role in (21), we examine below the sensitivity of our results to alternative values.

Vehicle operating cost

For vehicle operating costs, we concentrate on fuel consumption. This is likely to be the main component of vehicle operating costs which varies with traffic conditions (at least over the range that we consider).

According to engineering evidence for 9 cars from 1997 cited in Davis, Diegel, and Boundy (2008), a 20% increase in speed from about 40 to 48 km/h leads to a 5% decrease in fuel consumption, which implies an arc elasticity of around -0.25 for the speed elasticity of fuel consumption. This speed elasticity can then be multiplied by the elasticity of speed to highway lane kilometers, that is the opposite of the elasticity of time per kilometer to interstate lane kilometers, to obtain the relevant elasticity, $\rho_{Q^{\text{IH}}}^{VOC^{\text{AR}}}$. While we believe that 40 to 48 km/h is the relevant speed range to consider given the descriptive statistics for speed in table 5, we note that further increases in speed lead to first a flattening and then an increase in fuel consumption. For fuel consumption, we take 0.075 l/km. This is slightly above the numbers reported in the NPTS. Then we value this fuel consumption at the average price across US states of 0.37 \$/l for 2001. With these values, we obtain \$ 0.03 per kilometer for 2008.

Viewed differently and using (22), this cost of \$ 0.03 per kilometer multiplied by the speed elasticity of consumption of 0.25 can be added to TC^{AR} before multiplying it by $\rho_{Q^{\text{IH}}}^{TC^{\text{AR}}}$. This added quantity is less than \$ 0.01 per kilometer relative to our value of about \$ 0.26 for the time cost. This suggests that our calculation is not sensitive to the assumptions made for vehicle operating costs. Even a tripling of fuel prices would make little difference here.

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[24] There is a tiny difference in that table 6 uses a cost measured in units of time as opposed to a dollar cost. The OLS estimates for the dollar cost elasticity are the same. We are not confident that our instrumentation strategy works for dollar costs per kilometers since we expect our instruments to affect local earnings through channels other than VKT.

A welfare calculation

We can now compute the upper bound for Δw given by (20) and (22) for 228 MSAs. Taking $\rho^{TC^{\text{AR}}}_{Q^{\text{IH}}} = -0.06$, we find that the MSA mean of the upper bound on the welfare gain for an extra lane kilometer of highway is $227,000 by year. Unsurprisingly, there is considerable cross-MSA variation in this upper bound, with values around or below $40,000 for Great Falls (MT), Casper (WY), and Lawton (OK) and values near or above $600,000 for Chicago, Miami, Washington, San Francisco, and West Palm Beach.

We now turn to the cost of new lane kilometers of highways. Duranton and Turner (2008) use data from the US Federal Government, to argue for an annual cost per kilometer of $450,000 for maintenance of interstates. With an MSA average of 4.5 lanes by highway, this figure suggests an annual maintenance cost per lane kilometer around $100,000. For estimates of construction costs, we rely on figures recently proposed by Ng and Small (2008). For 2006, the total costs of an extra lane kilometer of expressways are m$3.64 for MSAs with a population less than 200,000, m$5.34 for MSAs with a population between 200,000 and 1 million, and m$11.96 for MSAs with a population greater that 1 million. Taking a cost of capital of 5% per year, these figures imply an MSA average capital cost of $419,000 per year per lane kilometer of interstate. Hence, on average the cost of an extra lane kilometer of highway is about $519,000 annually, or more than twice as large as the average upper bound of the welfare gain from a lane kilometer of interstate.

The difference between costs and the upper bound of welfare is, of course, not the same across MSAs. The lower bound on net welfare losses associated with a kilometer of interstate highway is around $500,000 for the bottom five cities: Rochester (NY), Grand Rapids (MI), Oklahoma City (OK), Greensboro (NC), and Las Vegas (NV). Only five MSAs would experience a net maximum welfare gain of an average $70,000. They are West Palm beach and Fort Myers in Florida, Providence, San Francisco and Colorado Springs. Interestingly, the largest MSAs are not all doing well here because of their much higher construction costs.

$\rho^{TC^{\text{AR}}}_{Q^{\text{IH}}}$ must reach an implausible -0.111 for the mean difference between costs and maximum gains to become positive on average. In sum, under our preferred set of assumptions, the costs of an extra kilometer of interstate exceeds its maximum benefits by a factor of more than two. It is only when we double the elasticity of speed to highway provisions that we can recover those costs. Hence, even though US interstates are increasingly busy and congested, an across-the-board expansion would yield small welfare gains relative to the costs.

Clearly this conclusion does not mean that no new road should ever be built or that no road should ever be enlarged. The removal of bottlenecks on busy roads, or other similar expansions, may lead to sufficient time gains to justify the investment. While we may conjecture about whether the positive external benefits of investments in new interstates are large enough to justify their construction, savings of transportation costs alone do not.

7. Conclusion

This paper analyzes new data describing city level traffic in the continental US between 1983 and 2003. By exploiting the fact that our data describe urbanized and non-urbanized area interstates along with urban roads, we not only confirm the 'fundamental law of highway congestion' suggested by Downs (1962), but also provide evidence that this law extends beyond urban highways. That is, our data suggests a 'fundamental law of road congestion' where the extension of most major roads is met with a proportional increase in traffic. Not only do we provide direct evidence for this law, but also show find evidence that three implications of this law; near flat demand curve for VKT, convergence of traffic levels, and no effect of public transit on traffic levels.

We also consider the sources of new traffic elicited by extensions to the interstate network. We find that changes to individual driving behavior and increases in trucking are most important. Migration is somewhat less important. Surprisingly, diversion of traffic from other road networks does not appear to play a large role. Importantly, our data provide little evidence that extensions of public transit will reduce traffic.

High levels of induced demand do not necessarily imply that improvements to the highway system are not in the public interest. However, our calculations suggest that an average extension of the interstate network does not result in sufficient travel time improvements to justify its cost. Two caveats apply here. First, our welfare calculation excludes some possible external benefits unrelated to travel time savings. Second, certain specific improvements of the system, for example inexpensive improvements to bottlenecks, may well be justified even if an across the board expansions are not.

A similar comment applies to public transit. The fact that increases in public transit do not reduce traffic does not imply that such improvements are not in the public interest. While we are not able to perform a welfare calculation to evaluate extensions to bus based public transit, we suspect on the basis of earlier research (Kain, 1999, Duranton and Turner, 2008) that improvements to bus-based public transit are often welfare improving.

We make two final remarks in closing. First, throughout our analysis we find that our instrumental variables estimations show find a similar relationship between roads and traffic as does OLS. Positing the validity of our instruments, this suggest that the assignment of roads to MSAs is unrelated to traffic (conditional on control variables). If true, this almost certainly results in lower welfare than would assigning roads to places with higher traffic levels. Second, we note that this research eliminates both capacity expansions and extensions to public transit as policies to combat traffic congestion. On the other hand, our estimates of the demand for VKT indicate that VKT is quite responsive to price. Together, these findings strengthen the case for congestion pricing as a policy response to traffic congestion.

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